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Report No. 5040-27

CG-D-11-77
June 1977

COMPUTER PROGRAM FOR
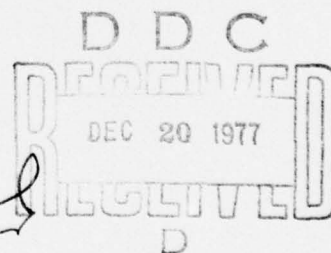DESIGN AND PERFORMANCE ANALYSIS
OF NAVIGATION-AID POWER SYSTEMS

Program Summary

June 1977

Final Report

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Prepared for

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
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Report No. 5040-27

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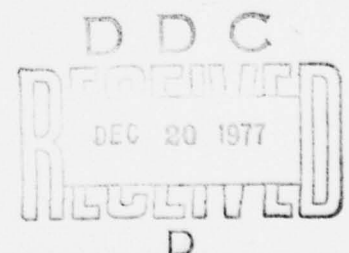
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The contract under which this report was prepared was under the technical supervision of the Coast Guard Research and Development Center, Groton, Connecticut 06340. R&D Center Report Number 18/76 has been assigned. *(DESIGN SYNTHESES/PERFORMANCE ANALYSES)

16. Abstract

A computer program developed for the performance analysis of a spacecraft power system by the Jet Propulsion Laboratory has been adapted to meet certain needs of the United States Coast Guard. This program, now designated as the Design Synthesis/Performance Analysis (DSPA) Computer Program is capable of performing all the calculations necessary to understand the overall characteristics of solar array-battery power systems for application to aids to navigation. The DSPA Computer Program will enable the Coast Guard to design solar array/battery power systems for aids to navigation having any specific flashing lamp load and at any geographical location, simulate the performance of solar array/battery power systems in operation on navigational aids under specific flashing lamp load and environmental conditions, and provide specifications for viable alternative designs which may be used to integrate solar array/battery power systems into the Coast Guard inventory. The DSPA Computer Program was verified by comparing the predicted operational characteristics of specified power systems with the actual performance of these same power systems. The Computer Program accurately predicted the changes in battery state-of-charge over a one year period for two power systems considered successfully tested by the Coast Guard. Three other power systems evaluated by the Coast Guard experienced erratic solar array degradation profiles during the one year test period and were considered as failures by the Coast Guard. Despite the uncertainties in the erratic solar array degradation data and the potential impact on actual battery behavior, verification test cases were performed, and the DSPA accurately predicted state-of-charge for two of the three systems. Verification of the DSPA was considered as successful based upon these results.

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*First page of each Appendix contains a list of figures.

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1. INTRODUCTION AND SUMMARY

A major mission of the U.S. Coast Guard is the task of providing and maintaining Maritime Aids to Navigation. These aids are located on and near the coast line and inland waters of the United States and its possessions. A specific type of navigational aid (flashing lamp on a buoy) offers a possible application for low-cost solar array/battery power systems.

Presently, flashing lamp buoys are powered by zinc-air batteries which require periodic replacement (1-2 year life). Development of a solar array/battery power system with unattended operation during a six-year life, shows considerable promise for reducing buoy maintenance costs.

Buoys are exposed to a wide variety of environments. The range of these environments are typified by weather conditions in locations at Fairbanks, Alaska, and Florida coastal waters. Operational and design problems are compounded when it is realized that solar-powered buoys must operate with a wide range of solar insolation in addition to functioning under a variety of weather conditions.

The Coast Guard has a requirement for a computer program capable of performing all the calculations necessary to understand the overall characteristics of solar array/battery power systems for application to Aids to Navigation. This report contains a description of the Design Synthesis/ Performance Analysis (DSPA) Computer Program developed by the Jet Propulsion Laboratory in response to the Coast Guard requirements.

The description of the DSPA Computer Program is presented as indicated below:

- Segment A - Program Summary.
- Segment B - Program Documentation.
  - Volume I - Software Requirements Document.
  - Volume II - Users' Manual.
  - Volume III - Programmer's Manual.

The DSPA Computer Program will enable the Coast Guard to:

- Design solar array/battery power systems for aids to navigation having any specific flashing lamp load and in any geographical location.

- Simulate the performance of solar array/battery power systems in operation on navigational aids under specific flashing lamp loads and environmental conditions.

- Provide specifications for viable alternative designs which may be used to integrate solar array/battery power systems into the Coast Guard inventory.

The specifications generated by the DSPA computer program may also be used by the Coast Guard as a basis for a complete economic analysis of alternative power system design.

The basis for selecting the computer program that will meet the Coast Guard requirements was determined by an examination of the uses of power system programs. Generally, power system computer programs are used for two types of system problems, i.e.,:

- Design Synthesis.
- Performance Analysis.

During design synthesis, load and environmental profiles set the requirements for the power system. Based on these requirements and on the electrical characteristics of the system equipment, the computer program determines the electrical size (volts, amperes, watts, ampere-hours, watt-hours) and the physical characteristics (weight, area, and cost) of the power system. A design synthesis computer program can also provide an easy means of determining sensitivities of the power system physical characteristics to variations in the many equipment parameters - in order to establish the rationale for "optimum" power system designs.

During performance analysis calculations, the arrangements, electrical size, and physical characteristics of power system equipment are already known. The objective, in this case, is to determine the response (or operational characteristics) of the power system equipment to a given

stimulus (load and environmental profiles). The performance analysis computer program provides a means of "measuring" and adjusting steady state performance (and transient performance if the selected profile time increments are small enough) of proposed or existing power systems in order to establish designs which meet system requirements.

The determination was made that Coast Guard objectives and requirements would be best attained if the computer program combined the features of both the design synthesis and performance analysis processes. A particularly critical requirement for determining the actual daily remaining battery capacity during a one year period was particularly amenable to solution by the performance analysis methodology.

The design synthesis methodology allows the program user to select a lamp and flasher combination as well as a particular power system arrangement (out of a limited set). The user must also supply information on daily cloud cover for periods of one week up to fifty two (52) weeks. Based on this information, the computer program determines the hourly solar insolation as well as the day/night load durations needed for a power load profile. (An alternative form of calculation utilizes solar insolation data taken from National Oceanic and Atmospheric (NOAA) solar radiation tapes). The power load profile, after modification using battery charge-efficiency and a number of power system cabling and diode losses, is used in the load profile analysis. The object of a load profile analysis is to determine the electrical size of a balanced* power source as well as the minimum theoretical electrical size of a battery. Once this information is obtained, it is a fairly simple and straightforward process to determine the electrical size of the remaining items of equipment since the design synthesis methodology is a linear step-by-step procedure.

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*Balanced power source: - power source which provides just enough energy to the batteries (during recharge periods) to offset or balance the energy loss sustained by the batteries during periods of discharge.

The methodology used in performance analysis* is to obtain the raw power bus operating point for each selected time increment during a mission. Once this operating point is obtained, all power system operational characteristics are easily determinable.

To obtain the operating point, the power system is divided into groups about the operating point node. These groups and the equipment in each group are:

Power Source Group:

- Solar Array.
- Shunt Limiter.
- Solar Array Isolation Diodes.
- Solar Array Cable.

Energy Storage Group:

- Batteries.
- Battery Chargers.
- Battery Isolation Diodes.
- Battery Cables.

Power Conditioning and Distribution Group:

- User Loads.
- Load Cable.

Current-voltage (I-V) characteristics of each equipment group are determined. The Power Conditioning and Distribution Group characteristics are then deducted from those of the Power Source Group to obtain a Difference Curve. The intersection of the Difference Curve with the Energy Storage Group characteristics (as determined by the computer program) is an estimate of the voltage and current on the raw power bus (operating point). During the time increment under examination, the battery is in a state of charge, discharge or open-circuit, depending on the value and sign of the operating point current. After the operating point is obtained, the operational characteristics of the power system equipment are determined. The computer program is then ready for examination of power system response for the next time increment. The process is repeated until the end of the mission of interest.

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*This portion of the DSPA Computer Program is based upon a similar program developed for the analysis of planetary spacecraft power systems by the JPL and for the National Aeronautics and Space Administration.

The computed results of both design synthesis and performance analysis are printed out in easily readable and comprehensive tabular formats. Additionally, an optional graphical summary of selected performance analysis output data is available as an aid in determining performance trends.

A selection of key data used to represent the performance characteristics of the equipment was compiled and also presented. This program data is conveniently placed in the three categories representative of the equipment functions, i.e.,:

- Power Source Group.
- Energy Storage Group.
- Power Conditioning and Distribution Group.

The final phase of DSPA Computer Program development was program verification. This phase was necessary to provide a check on the validity of the performance analysis methodology used in the program by comparing the predicted operational characteristics of a known power system with the actual operational performance of that same power system. During this phase, data on the critical parameters of five power systems, undergoing test at the USCG Research and Development Center, Groton, Conn., were supplied by the Coast Guard.

The DSPA Computer Program accurately predicted the change in battery capacity over a one year period for the two power systems considered successfully tested by the Coast Guard. The other three power systems experienced erratic solar array performance and were considered failures by the Coast Guard. In spite of these problems, the DSPA fairly well predicted the battery capacity over a one year period for two of the three "failed" power systems.

2. COMPUTER PROGRAM DESCRIPTION

The features of the DSPA Computer Program are discussed in this section of the program summary. The key elements of this discussion include specific program requirements, computer program rationale, DSPA Computer Program, design synthesis and performance analysis. These elements are presented below.

2.1 Specific Program Requirements

The major requirements of the DSPA Computer program, as discussed in the Introduction were to provide a capability to:

a. Design solar array/battery power systems for aids to navigation having any specific flashing lamp load and at any geographical location.

b. Simulate the performance of solar array/battery power systems in operation on Navigational Aids using specific flashing lamp loads, at any geographical location and under specific environmental conditions.

c. Determine specification for viable alternative designs which may be used to integrate solar array/battery power systems into the Coast Guard inventory.

Additionally, there were specific requirements that the DSPA Computer Program have the following features:

d. Program flexibility to accept data on solar insolation, wind and wave motion. It was intended that the program be written with enough flexibility so that power system design analysis can be determined for systems using solar insolation, wind or wave motion as the primary energy sources. The initial version of the computer program, however, was only required to utilize solar array power sources with the capability of easily adding subprograms which utilize the characteristics of wind-powered or wave motion power generators.

e. Ability to generate solar insolation values at any latitude and longitude.

f. Capability of accepting input parameters such as temperature, hours of sunlight, load characteristics, and cost factors. JPL was further required to identify any additional input parameters needed for program operation. As an example, the use of this computer program for both buoys and shore stations was desired. In the case of buoys, the effects of wind/wave motion on array power output (and other characteristics) were to be ignored. The assumption was to

be made that all buoy solar arrays are horizontal. Shore station arrays, on the other hand, would be southfacing and tilted at some "optimum" angle (e.g., tilt angle ∿ latitude). Hence, the computer program was coded to accept any preselected solar array tilt angle.

g. Program modular design, wherein the characteristics of each equipment module could be readily included, deleted, or changed by the computer program operator. Equipment modules include solar cell panels, batteries, battery chargers, shunts, etc. The program operator, for example, could select the type of shunt desired, i.e., none, ordinary zener diode, temperature-compensated zener diode or active type. Characteristics of all of these shunt types are part of the normal program data which may be modified by the program operator as new characteristics are determined.

h. Automatic design operations with the capability of allowing the program operator to specify variable operating parameters and design criteria. Examples of design criteria over which the operator must have control include:

   1) Minimum remaining acceptable battery capacity.

   2) Inclusion of restrictions on solar array and battery sizing.

   3) Inclusion of safety factors.

   4) Selection of system elements.

i. Perform calculations which take into consideration all parameters affecting useable stored battery capacity. Examples of these parameters, listed below, are typically obtained from analyses of power system operational characteristics.

   1) Solar Array current-voltage characteristics as a function of solar insolation magnitude and cell temperature.

   2) Voltage Regulator: Voltage cut-off characteristic as a function of input voltage and temperature.

   3) Storage Battery: Lifetime degradation characteristics (cycle life) of the battery as a function of depth of discharge.

j. Capability of storing or generating the total range of operating characteristics of all possible system elements.

k. Ability to accept various restrictions on power system operations. Examples of these restrictions are:

   1) Minimum battery temperature as a function of remaining capacity. Information on freezing temperatures are generally obtained from data of the type shown in Figure 2-1.
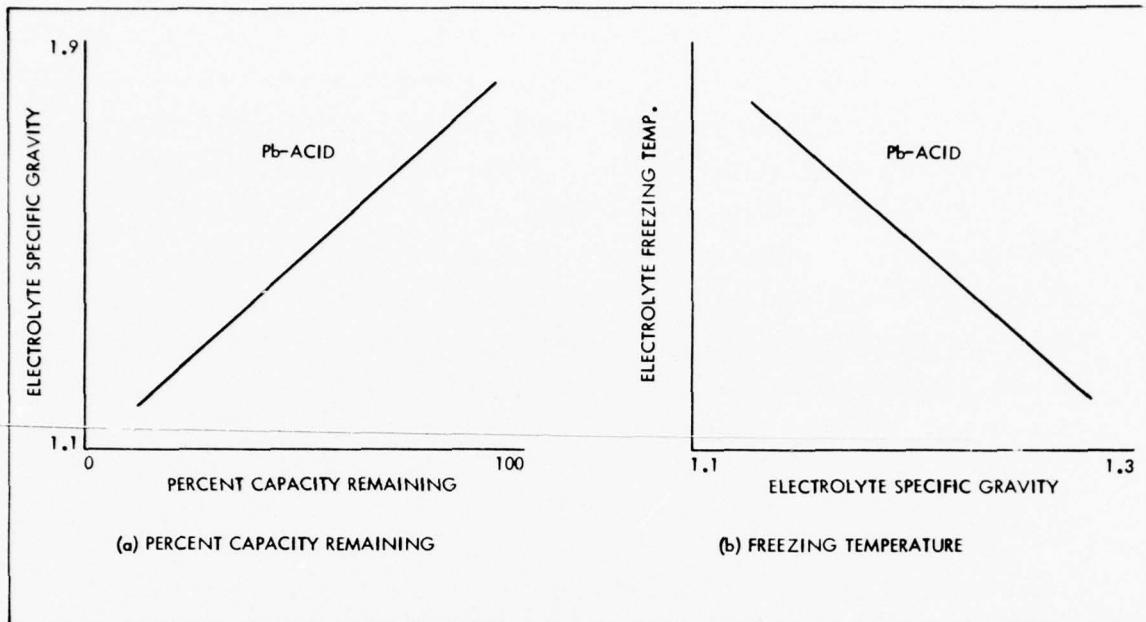
FIGURE 2-1. BATTERY ELECTROLYTE FREEZING TEMPERATURE AS FUNCTION OF REMAINING CAPACITY

   2)   Minimum allowable remaining battery capacity.

   3)   Maximum time allowable with the battery capacity below a given value.

l.   Program Outputs. The primary program output must be a table which shows actual remaining battery capacity for each day over a one to two year period. This is the central and critical requirement for the entire computer program. The computer program must be capable of dealing with a one year load/environmental/solar insolation profile for a reasonable running cost.

m.   Program Language. The computer program must be written in FORTRAN-V for use on a UNIVAC-1108 Computer. Such a computer is available to personnel from the U.S. Coast Guard R&D Center, Avery Point, Conn., and is located at the Naval Underwater Systems Center (NUSC), New London, Conn.

2.2 Computer Program Rationale

The basis for selecting the proper computer program that will meet the Coast Guard requirements was determined by an examination of the uses of power system programs. Generally, power system computer programs are used for two types of system problems, i.e.,:

        ● Design Synthesis.
        ● Performance Analysis

2-3

In design synthesis, load and environmental profiles set the requirements for the power system. Based on these requirements and on the electrical characteristics of the system equipment, the computer program determines the electrical size (volts, amperes, watts, ampere-hours, and watt-hours) and the physical characteristics (weight, area, cost) of the power system. A design synthesis computer program can also provide an easy means of determining sensitivities of the power system physical characteristics to variations in the many of the equipment parameters-in order to establish the rationale for "optimum" power system designs. Some of the more flexible design synthesis programs may even select the "optimum" arrangments of power system equipment, rather than leaving the choice of such arrangements to the program operator.

In performance analysis calculations, the arrangements, electrical size and physical characteristics of power system equipment are already known. The objective, in this case, is to determine the response (or operational characteristics) of the power system equipment to a given stimulus (load and environmental profiles). The performance analysis computer program provides a means of "measuring" and adjusting steady-state performance (and transient performance if the selected profile time increments are small enough) of proposed or existing power systems in order to establish designs which meet system requirements.

A number of methods for performance analysis of circuits and modules have been developed in the past. Usually, these take the form of nodal analyses in which the transfer function of a circuit, part, or component is analyzed in a complex network whose branch interconnection points or nodes are reference points. A voltage or current is assumed for each node, the entire circuit solved by solution of simultaneous equations, and the values of voltage and current at each node compared with the assumed values. If they are not the same, the computed values replace the initial assumptions, and the solution is repeated. After a number of iterations, the system eventually converges, and the final solution is reached. If the system consists of more than a very few nodes, the problem is solvable only in a computer and with large numbers of nodes. Even the computer programs can become too costly to use because of the increasing number of iterations required to reach a final convergence. When these problems are

added to the necessity for possible thermal solutions at each moment in time, use of nodal analysis programs for describing the performance of power subsystems containing batteries presents a discouraging picture.

The approach herein to Performance Analysis, discussed in Section 2.5 below, represents an achievable compromise between the desirable complete electrical analysis given by the nodal analysis type of program and the excessive cost and complexity of detailed nodal analysis. The compromise approach (to Performance Analysis) uses a graphical analysis method which is implemented for the computer and which also lends itself to more accurate modeling of battery current-voltage characteristics.

The determination was made that Coast Guard objectives and requirements would be best attained if the computer program combined the features of both the design synthesis and the compromise approach to performance analysis processes. The particularly critical requirement for determining the actual daily remaining battery capability during a one year period was particularly amendable to solution by the "compromise" performance analysis methodology.

Accordingly, the computer program actually developed was one which combines the elements of design synthesis and performance analysis and was named the Design Synthesis Performance Analysis (DSPA) Computer Program.

2.3 DSPA Computer Program

The generalized arrangement of the solar array/battery power system used as the basis of the DSPC Computer Program is shown in Figure 2-2. Basically, the system contains the following major elements:

- Solar array.
- Shunt Limiter.
- Battery charger.
- Battery.
- User Loads.
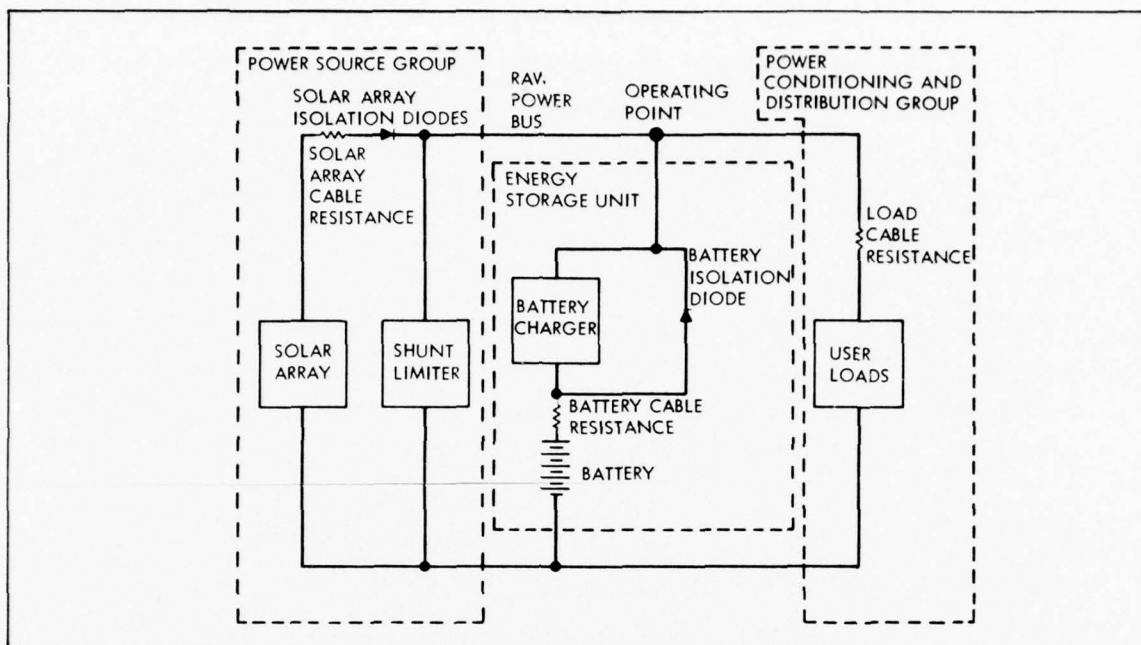
FIGURE 2-2. POWER SYSTEM BLOCK DIAGRAM

Solar arrays are the primary power source, providing for the photovoltaic energy conversion of sunlight into electrical power. The array must be large enough to provide sufficient power for the user loads, power system "housekeeping" losses, and battery charging during periods of solar insolation.

A shunt limiter may be provided to limit the maximum voltage on the raw power bus. The shunt limiter is usually designed to accept the full output power of the solar array.

Batteries are needed to provide power during periods when the user loads require more power than is available from the solar array as well as for providing power during periods of solar occultation. The minimum voltage on the raw power bus is determined by the minimum battery voltage.

Battery chargers may also be used in the process of restoring energy to a discharged battery. The function of the charger is to maintain battery voltage and current within tolerable levels during the charging process.

The user loads consist of a flashing lamp (utilized on a buoy) as well as a regulator to control the current voltage and phasing of that lamp.

An important concept in power system operation and analysis is that of the the operating point, i.e., the nodal point in the power circuit about which the major elements of the power system are grouped. As an aid in design and analysis, the system elements are divided into three major groups about the operating point node.

- <u>Power Source Group:</u>

    Solar Array.
    Shunt Limiter.
    Solar Array Isolation Diodes.
    Solar Array Cable.

- <u>Energy Storage Group:</u>

    Batteries.
    Battery Chargers.
    Battery Isolation Diodes.
    Battery Cables.

- <u>Power Conditioning and Distribution Group:</u>

    User Loads.
    Load Cable.

The Energy Storage Group consists of parallel Energy Storage Units. A single Energy Storage Unit, as shown in Figure 2-2, contains a battery, battery charger, battery isolation diode and battery cables.

A functional block diagram of the Design Synthesis Performance Analysis (DSPA) Computer Program is shown in Figure 2-3. The DSPA Computer Program, at the primary level, utilizes the following methodology:

a. The program operator selects the power system arrangement desired.

b. If a design synthesis <u>is</u> <u>not</u> required, then the program operator must provide information on the electrical size of the equipment selected.

c. If a design synthesis <u>is</u> requested, the program operator must supply information on the parameters used in determining the various profiles. The computer program then calculates the load and environmental profiles needed in their entirety for a load profile analysis. Based on a profile energy balance determined as part of the load profile analysis, the computer estimates the electrical size of the equipment selected.
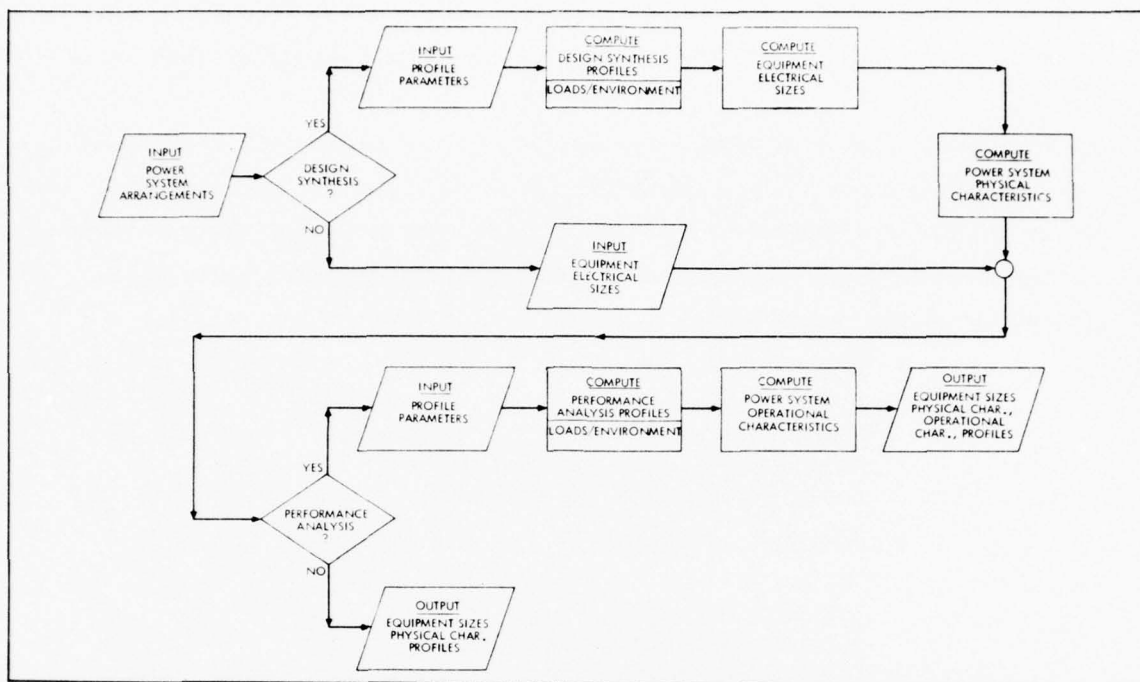
FIGURE 2-3. DESIGN SYNTHESIS PERFORMANCE ANALYSIS COMPUTER PROGRAM

d. The physical characteristics of the equipment selected is then determined by the computer, based on the equipment electrical size.

e. If performance analysis is not required, the data calculated by the program, along with the input data, is printed in the appropriate output data format.

f. If performance analysis is requested, the program operator must again supply information on the parameters used in determining the various profiles. The computer program then calculates the values of the load and environment at the start of a selected mission period. These stimuli (load, environment) are used to calculate the response (operational characteristics) of the equipment at that point in time. The process is repeated for selected time increments until the power system operational characteristics for the entire mission period have been determined. This information is then printed in the appropriate output data format.

An overview of the input/output elements of the DSPA Computer Program is shown in Figure 2-4. Input data requirements fall into two major groups, i.e., Program Parameter Data and Environmental Profiles.

Program Parameter Data contains information on mission requirements (latitude, longitude, duration, etc) and equipment characteristics.
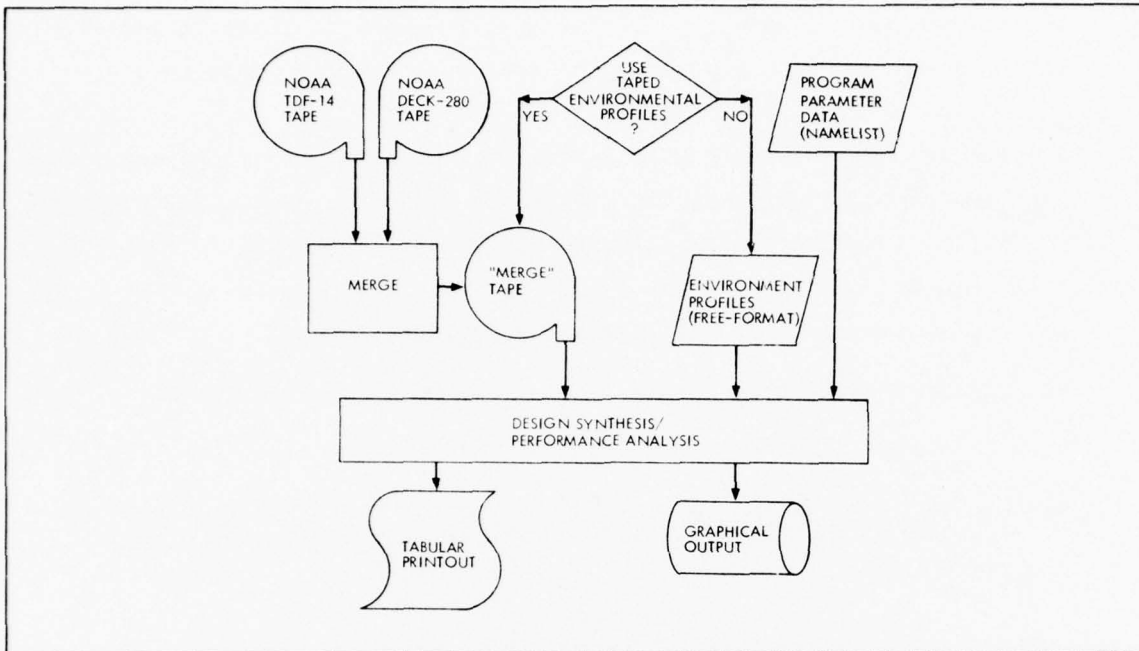
FIGURE 2-4.   DSPA COMPUTER PROGRAM INPUT/OUTPUT

These data are required in a "Namelist" format - for ease in changing
values of the parameters for repetitive computer runs.

Environmental Profiles are obtained from two sources. The program user
may elect to prepare his own cloud cover profile (in Free-Format) for
use in estimating solar insolation, or he may elect to use the actual
solar insolation values for a given location directly from a "MERGE"
tape (described below).

After DSPA Computer Program calculations are completed, the output will
be printed in a tabular format. The program user may also elect to
receive a graphical output of the tabulated results.

Solar Insolation and other environmental information is available on
magnetic tapes from the National Climatic Center, National Oceanic and
Atmospheric Administration (NOAA) at Asheville, North Carolina. The
magnetic tapes of particular interest are those for Surface Observations
(TDF-14; Reference 1) and Solar Radiation (DECK-280; Reference 2).

The information recorded on TDF-14 magnetic tapes is given in Table 2-1. Data recorded on Deck 280 magnetic tapes are shown in Table 2-2.

Since these tapes contain more information than was needed as input for the DSPA Computer Program, an independent "MERGE" program was developed to provide a simplified tape input. The "MERGE" program performs the following functions.

- Reads in data from the TDF-14 and Deck-280 tapes.

- Combines data into single, sequential random access files.

- Annotates empty data locations.

- Prepares a "MERGE" tape containing temperature, solar insolation and wind velocity as a function of time for various geographical locations.

"MERGE" tapes have been prepared for the ten principal coastal locations (shown in Table 2-3) and five supplemental locations (shown in Table 2-4) selected by the Coast Guard.

TABLE 2-1.—SURFACE OBSERVATIONS, TDF-14 INFORMATION RECORDED

Station Number	Drizzle	Blowing Spray
Year, Month, Day, Hour	Freezing Drizzle	Sea Level
Ceiling Height	Snow	Pressure
Sky Condition:	Snow Pellets	Dew Point
Clear	Ice Crystals	Temperature
Scattered	Snow Showers	Wind Direction
Broken	Snow Grains	Wind Speed
Overcast	*Sleet	Station Pressure
Partial Obscuration	Hail	Dry Bulb
Obscuration	*Small Hail	Temperature
Visibility	Fog	Wet Bulb
Weather and/or	Ice Fog	Temperature
Obstruction to Vision	Ground Fog	Relative Humidity
Thunderstorm	Blowing Dust	Total Sky Cover
Tornado	Blowing Sand	Amount, Type and
Squall	Smoke and/or	Height of Cloud
Rain	Haze	Layers
Rain Showers	Dust	Opaque Sky
Freezing Rain	Blowing Snow	Cover

*Reported as Ice Pellets, effective 1 Apr 70.

TABLE 2-2.—SOLAR RADIATION, DECK-280 INFORMATION RECORDED

Station Number
Year, Month, Day, Hour
Solar Radiation — Hemispheric (sum of direct and diffuse)
Solar Elevation
Extra-Terrestrial Radiation
Sunshine
Snow Cover
Solar Week (discontinued 1 Jan 63)
Opaque Sky Cover (discontinued 1 Jan 65)
Solar Hour
Percent of Possible Radiation (discontinued 1 Jan 65)
Visibility (discontinued 1 Jan 65)
Weather and/or Obstructions to Vision (discontinued 1 Jan 65)
Dry Bulb Temperature °F (discontinued 1 Jan 65)
Dew Point Temperature °F (discontinued 1 Jan 65)
Amount, Type and Height of Cloud Layers (discontinued 1 Jan 65)

2.4 Design Synthesis

A detailed picture of the design synthesis methodology is shown in Fig-
ure 2-5. This methodology allows the programmer user to select a lamp and
flasher combination as well as a particular power system arrangement (out
of a limited set). The user must also supply information on daily cloud
cover for periods of one week up to fifty two (52) weeks or, if so desired,
hourly solar insolation and temperature values from a "MERGE" tape for the
same periods of time. Based on this information, the DSPA Computer Pro-
gram determines the daily periods of solar occultation, power system share-
mode operation, battery charging and the number of battery operating mode
reversals (needed to estimate battery charge/discharge cycle requirements).
Using the information, a power load profile is obtained. The power load
profile, after modification using battery charge-efficiency and a number
of power system cabling and diode losses, is used in the load profile
analysis. The object of a load profile analysis is to determine the elec-
trical size of a balanced* power source as well as the minimum theoretical
size of a battery. Mathematical formulations for estimating the size of a

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*Balanced power source: -a power source which provides just enough energy to
the batteries (during recharge periods) to offset or balance the energy loss
sustained by the batteries during periods of discharge.

TABLE 2-3.—NOAA SOLAR/WEATHER TAPES

(Principal Locations)

Station Number	Station Name	NOAA Tape	Data Periods Covered
14607	Caribou, Maine	DK-280	Jan 1955 - Dec 1964
14607	Caribou, Maine	TDF-14	Jan 1955 - Dec 1964
14753	Blue Hill/Milton, Mass.	DK-280	Jan 1955 - Dec 1964
14739	Boston, Mass.	TDF-14	Jan 1955 - Dec 1964
94706	New York, N.Y., (Central Park)	DK-280 ⌉	Jan 1953 - Dec 1958
94706	New York, N.Y., (Central Park)	DK-280 ⌋	Jan 1963 - Dec 1966
14732	La Guardia Field, N.Y.	TDF-14 ⌉	Jan 1953 - Dec 1958
14732	La Guardia Field, N.Y.	TDF-14 ⌋	Jan 1961 - Dec 1964
14847	Sault Ste. Marie, Mich.	DK-280	July 1952 - Aug 1958
14847	Sault Ste. Marie, Mich.	TDF-14	Jan 1952 - Dec 1961
13745	Hatteras, N.C.	DK-280 ⌉	Jan 1955 - Mar 1957
93729	Cape Hatteras, N.C.	DK-280 ⌋	Mar 1957 - Dec 1964
13745	Hatteras, N.C.	TDF-14 ⌉	Jan 1955 - Mar 1957
93729	Cape Hatteras, N.C.	TDF-14 ⌋	Mar 1957 - Dec 1964
12839	Miami, Florida	DK-280	Jan 1955 - Dec 1964
12839	Miami, Florida	TDF-14	Jan 1955 - Dec 1964
12919	Brownsville, Texas	DK-280 ⌉	Jan 1953 - Dec 1955
12919	Brownsville, Texas	DK-280 ⌋	Jan 1959 - Dec 1965
12919	Brownsville, Texas	TDF-14 ⌉	Jan 1953 - Dec 1956
12919	Brownsville, Texas	TDF-14 ⌋	Jan 1959 - Dec 1964
23174	Los Angeles, Calif.	DK-280	Jan 1962 - Dec 1966
23174	Los Angeles, Calif.	TDF-14	Jan 1955 - Dec 1964
24233	Seattle, Wash.	DK-280	Jan 1955 - Dec 1964
24233	Seattle, Wash.	TDF-14	Jan 1955 - Dec 1964
26615	Bethel, Alaska	DK-280 ⌉	July 1952 - Oct 1952
26615	Bethel, Alaska	DK-280 ⌋	Dec 1956 - Apr 1957
26615	Bethel, Alaska	TDF-14	Jan 1952 - Dec 1961

balanced power source are given in Appendix A. The equations in Appendix A
form the basis for the key algorithms used in design synthesis.

Once the electrical size of a balanced power source is obtained, it is a
fairly simple and straight forward process to determine the electrical

TABLE 2-4.-NOAA SOLAR/WEATHER TAPES

(Supplemental Locations)

Station Number	Station Name	NOAA Tape	Data Periods Covered
13983	Columbia, MO.	DK-280	Jan 1955 - Dec 1964
13983	Columbia, MO	TDF-14	Jan 1955 - Dec 1964
23154	Ely, NV.	DK-280	Jan 1955 - Dec 1964
23154	Ely, NV.	TDF-14	Jan 1955 - Dec 1964
24225	Medford, OR.	DK-280	Jan 1955 - Dec 1964
24225	Medford, OR.	TDF-14	Jan 1955 - Dec 1964
93193	Fresno, CA.	DK-280	Jan 1955 - Dec 1964
93193	Fresno, CA	TDF-14	Jan 1955 - Dec 1964
93722	Silver Hill, MD.	DK-280）	Jan 1955 - Dec 1960
93734	Sterling, VA.	DK-280）	Dec 1960 - Dec 1964
13743	Wash. D.C. (Natl. Airport)	TDF-14	Jan 1955 - Dec 1964

size of the remaining items of equipment since the design synthesis
methodology is a linear step-by-step procedure.

The major elements (subroutines) of the design synthesis subprogram are
shown in Figure 2-6. Functions performed by each of the major subroutines
are also shown in this figure.

Examples of tabular output from design synthesis calculation are shown in
Figures 2-7 to 2-10. The output includes separate tabular parameters for:

- Design specifications and costs.

- Engineering Design Data.

- Battery Performance Data.

- Power Load Profile Analysis.

The first two of the presentation shows the costs, specifications and
major physical characteristics of the designed power system. The last
two presentations cover key information obtained during the design process.

FIGURE 2-5. POWER SYSTEM DESIGN SYNTHESIS

```
┌─────────────────────────────────────────────────────────────────────────┐
│   ┌──────────┐                                                           │
│   │ DSDRVR   │           MAIN DESIGN SYNTHESIS DRIVER PROGRAM            │
│   └────┬─────┘                                                           │
│        │     ┌──────────┐                                                │
│        ├─────│ DS-BATEFC│           COMPUTES BATTERY EFFICIENCY          │
│        │     └──────────┘                                                │
│        │     ┌──────────┐                                                │
│        ├─────│ DS-CDSI  │           COMPUTES CLEAR DAY SOLAR INSOLATION  │
│        │     └──────────┘                                                │
│        │     ┌──────────┐                                                │
│        ├─────│ DS-ESGIV │           COMPUTES BATTERY CURRENT AND VOLTAGE │
│        │     └──────────┘           CHARACTERISTICS                       │
│        │     ┌──────────┐           COMPUTES POWER CONDITIONING AND       │
│        ├─────│ DS-PCDGC │           DISTRIBUTION GROUP CURRENT AND        │
│        │     └──────────┘           VOLTAGE CHARACTERISTICS               │
│        │     ┌──────────┐                                                │
│        ├─────│ DS-SAEC  │           COMPUTES SOLAR ARRAY CURRENT AND     │
│        │     └──────────┘           VOLTAGE CHARACTERISTICS               │
│        │     ┌──────────┐           COMPUTES TERMINATOR CHARACTERISTICS   │
│        └─────│ DS-TERMC │           (SUNRISE AND SUNSET TIMES)            │
│              └──────────┘                                                │
└─────────────────────────────────────────────────────────────────────────┘
```
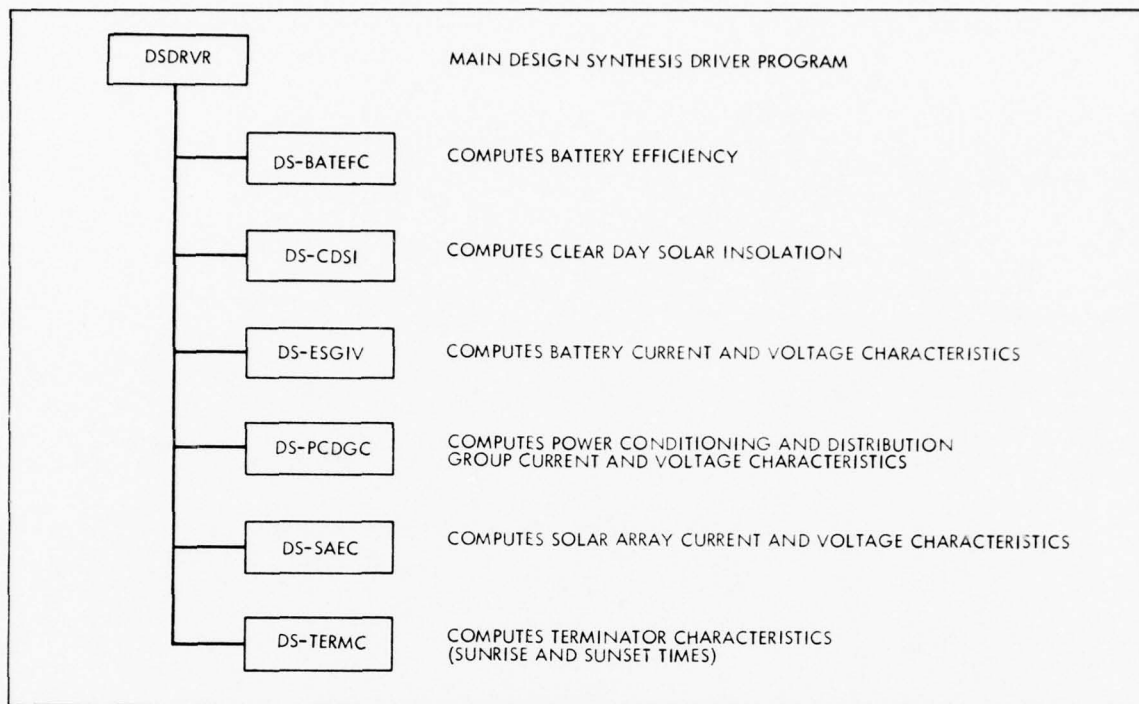
FIGURE 2-6.   DESIGN SYNTHESIS SUBPROGRAM ELEMENTS

2.5 Performance Analysis

A detailed picture of the performance analysis methodology is shown in
Figure 2-11. This portion of the DSPA Computer Program was based upon a
similar program developed by JPL for the analysis of planetary spacecraft
power systems (Reference 3).

The analysis of terrestrial power system performance is a complex task.
This complexity stems, in part, from the interaction of the power system
with the ambient environment. Batteries, for example, have electrical
characteristics which show significant variation with temperature. The
same is true of solar arrays. Hence, at a minimum, any reasonably accurate
simulation of power system operation must include ambient and equipment
temperatures as an independent parameter. An overview of the complexity
of the procedures necessary to analyze power system performance is indi-
cated in Figure 2-11. This figure shows the flow of data during the
calculation as well as the iterative nature of the procedures.

NAVIGATION AID POWER SYSTEM DESIGN CHARACTERISTICS

MISSION DURATION =	.6000+01 YEARS
DESIGN PERIOD =	52 WEEKS
NOMINAL OPERATING VOLTAGE =	.1200+02 VOLTS
SOLAR ARRAY SURFACE TILT ANGLE =	.0000 DEGREES
SOLAR ARRAY SURFACE AZIMUTH ANGLE =	.0000 DEGREES

BUOY LATITUDE =	.3393+02 DEGREES
BUOY LONGITUDE =	.1184+03 DEGREES
TIME ZONE NUMBER =	.8000+01
AVERAGE YEARLY TEMPERATURE =	.5890+02 DEG. FAHRENHEIT
MAXIMUM AMBIENT TEMPERATURE =	.8346+02 DEG. FAHRENHEIT
MINIMUM AMBIENT TEMPERATURE =	.4066+02 DEG. FAHRENHEIT

DESIGN PERIOD LOAD ENERGY REQUIREMENTS (WATT-HOURS)

FOR SOLAR OCCULATION: .3141+04   FOR SHARE-MODE OPERATION: .1748+01   FOR BATTERY-CHARGING PERIODS: .2022+03

USER SYSTEM REQUIREMENTS

FLASHER PATTERN TYPE =	3
FLASHER PATTERN =	.4, 3.6.
SOLAR INSOLATION LEVEL FOR LAMP-FLASHER TURN-ON =	.1386+00 WATTS/SQ. METER
SOLAR INSOLATION LEVEL FOR LAMP-FLASHER TURN-OFF =	.6932+00 WATTS/SQ. METER
POWER CONDITIONING AND DISTRIBUTION GROUP LAMP-FLASHING CURRENT =	.6122-01 AMPERES
POWER CONDITIONING AND DISTRIBUTION GROUP LAMP-OFF CURRENT =	.3780-02 AMPERES
POWER CONDITIONING AND DISTRIBUTION GROUP LAMP-FLASHING LOAD =	.7346+00 WATTS
POWER CONDITIONING AND DISTRIBUTION GROUP LAMP-OFF LOAD =	.4537-01 WATTS

INDIVIDUAL POWER SYSTEM CHARACTERISTICS

SUBSYSTEM	TYPE	NO. TO BE PROCURED	WEIGHT (POUNDS)	AREA (SQ. FEET)	COST ($)
POWER SOURCE GROUP					
SOLAR ARRAY	0	1000	.1993+01	.7381+00	.1652+03
SHUNT LIMITER	0	0	.0000		.0000
ENERGY STORAGE GROUP					
BATTERY	0	1000	.1219+03		.1583+03
CHARGER	0	0	.0000		.0000
TOTALS			.1238+03		.3235+03

FIGURE 2-7. DESIGN SPECIFICATIONS AND COSTS

SUMMARY OF ENGINEERING DESIGN DATA
FOR NAVIGATION AID POWER SYSTEM

MISSION DURATION = .6000+01 YEARS   POWER SOURCE GROUP ENERGY REQUIREMENT = .4256+04 WATT-HOURS
DESIGN PERIOD = 52 WEEKS   SOLAR ARRAY ENERGY REQUIREMENT = .4610+04 WATT-HOURS
MAXIMUM SOLAR RADIATION = .9652+03 WATTS/SQ. METER   MAXIMUM SOLAR ARRAY POWER = .5348+01 WATTS
TOTAL DESIGN PERIOD SOLAR RADIATION = .1772+07 WATT-HOURS/SQ.METER   AVERAGE POWER SOURCE GROUP POWER = .9544+00 WATTS

POWER SOURCE GROUP

SHUNT LIMITER:
    TYPE OF SHUNT LIMITER = 0

SOLAR ARRAY:
AREA OF A SINGLE SOLAR CELL = .4000+01 SQ. CENTIMETERS
NO OF SOLAR CELLS IN PARALLEL = 1
NO. OF SOLAR CELLS IN SERIES = 30
NO. OF ELECTRICAL SECTIONS IN PARALLEL = 4
TOTAL NO. OF SOLAR CELLS = 120
SOLAR ARRAY RESERVE FRACTION = .2000+00
ELECTRICAL SECTION BLOCKING DIODE RATING = .1028+00 WATTS

ENERGY STORAGE GROUP

CHARGER:
    TYPE OF CHARGER = 0
    MAXIMUM LOAD FOR A SINGLE CHARGER = .0000 WATTS

BATTERY:
NO. OF STORAGE CELLS IN SERIES = 6
NO. OF BATTERIES IN PARALLEL = 3
BATTERY RESERVE FRACTION = .5000+00
DISCHARGE CAPACITY FOR A SINGLE BATTERY = .5000+02 AMP-HOURS
TOTAL DISCHARGE CAPACITY FOR ALL BATTERIES = .1500+03 AMP-HOURS
MAXIMUM CHARGING CURRENT FOR A SINGLE BATTERY = .5000+01 AMPERES
TOTAL BATTERY ENERGY = .1583+04 WATT-HOURS

FIGURE 2-8. ENGINEERING DESIGN DATA

POWER LOAD PROFILE AND BATTERY PERFORMANCE ANALYSIS

BATTERY RESERVE FRACTION =   .5000+00
STANDARD NORMALIZED BATTERY DISCHARGE CURRENT =   .5000-01 AMPERES/AMP-HR
STANDARD BATTERY DISCHARGE TEMPERATURE =   .7000+02 DEG. FAHRENHEIT
BATTERY CHARGER TURN-ON INPUT VOLTAGE =   .0000   VOLTS
BATTERY CHARGER SATURATED-TO-ACTIVE INPUT VOLTAGE =   .0000   VOLTS

TOTAL MISSION BATTERY CYCLE REQUIREMENTS =   2185
THEORETICAL DEPTH-OF-DISCHARGE =   .1000+01
MAXIMUM ALLOWABLE CHARGING CURRENT FOR A SINGLE BATTERY =   .5000+01 AMPERES
ACTUAL DEPTH-OF-DISCHARGE =   .4842+00
TOTAL BATTERY ENERGY =   .1583+04 WATT-HOURS

THEORETICAL DISCHARGE ENERGY REQUIREMENT =   .7663+03 WATT-HOURS
DISCHARGE ENERGY USING CRITERION NO. 1 =   .1533+04 WATT-HOURS
DISCHARGE ENERGY USING CRITERION NO. 2 =   .7663+03 WATT-HOURS
DISCHARGE ENERGY USING CRITERION NO. 3 =   .4642+02 WATT-HOURS
SELECTED DISCHARGE ENERGY CAPACITY =   .1533+04 WATT-HOURS

FIGURE 2-9. BATTERY PERFORMANCE DATA

WEEK INDEX	NO. OF MODE REVERSALS	SOLAR OCCULTATION (HOURS)	***** WEEKLY DURATION OF ***** SHARE-MODE OPERATIONS (HOURS)	CHARGING PERIODS (HOURS)	WEEKLY TOTAL OF SOLAR INSOLATION (WT-HRS/SQ.M)	WEEKLY SOLAR INSOLATION MAXIMUM (WATTS/SQ.M)	BATTERY DISCHARGE ENERGY DURING SOLAR OCCULTATION (WATT-HOURS)	SHARE-MODE OPERATIONS (WATT-HOURS)	CHARGING PERIODS (WATT-HOURS)
1	14	.9875+02	.5367-01	.6818+02	.1784+05	.5075+03	.7255+02	.3939-01	.2437+02
2	14	.9908+02	.5725-01	.6885+02	.1711+05	.5164+03	.7279+02	.4202-01	.2316+02
3	14	.9903+02	.4861-01	.6891+02	.2207+05	.5310+03	.7275+02	.3567-01	.2760+02
4	14	.9860+02	.5018-01	.6934+02	.1998+05	.5512+03	.7243+02	.3682-01	.2761+02
5	14	.9778+02	.5218-01	.7016+02	.1991+05	.5761+03	.7183+02	.3830-01	.2787+02
6	14	.9660+02	.4355-01	.7135+02	.2410+05	.6048+03	.7097+02	.3196-01	.3483+02
7	14	.9510+02	.4460-01	.7285+02	.2450+05	.6360+03	.6987+02	.3273-01	.3519+02
8	14	.9333+02	.4646-01	.7462+02	.2472+05	.6680+03	.6856+02	.3410-01	.3743+02
9	14	.9134+02	.3916-01	.7662+02	.2982+05	.7388+03	.6710+02	.2874-01	.4692+02
10	14	.8919+02	.4077-01	.7877+02	.3280+05	.8276+03	.6552+02	.2992-01	.5333+02
11	14	.8693+02	.4334-01	.8102+02	.3370+05	.8580+03	.6386+02	.3181-01	.5643+02
12	14	.8463+02	.3735-01	.8332+02	.3449+05	.8227+03	.6217+02	.2741-01	.6039+02
13	14	.8234+02	.3975-01	.8561+02	.3855+05	.9059+03	.6049+02	.2917-01	.6866+02
14	14	.8011+02	.4314-01	.8744+02	.3951+05	.9233+03	.5885+02	.3165-01	.7227+02
15	14	.7797+02	.3745-01	.8998+02	.3909+05	.8714+03	.5728+02	.2777-01	.7322+02
16	14	.7598+02	.4089-01	.9197+02	.4364+05	.9463+03	.5581+02	.3000-01	.8432+02
17	14	.7415+02	.4448-01	.9380+02	.4386+05	.9533+03	.5447+02	.3293-01	.8602+02
18	14	.7250+02	.3971-01	.9544+02	.4199+05	.8915+03	.5326+02	.2914-01	.8369+02
19	17	.7106+02	.4312-01	.9688+02	.4462+05	.9613+03	.5220+02	.3164-01	.9467+02
20	17	.6983+02	.4747-01	.9810+02	.4620+05	.9633+03	.5130+02	.3483-01	.9497+02
21	17	.6882+02	.4202-01	.9912+02	.4385+05	.8975+03	.5056+02	.3083-01	.9091+02
22	17	.6804+02	.4557-01	.9990+02	.4836+05	.9651+03	.4998+02	.3344-01	.1014+03
23	17	.6748+02	.5002-01	.1005+03	.4760+05	.9652+03	.4957+02	.3670-01	.1003+03
24	17	.6715+02	.4407-01	.1008+03	.4488+05	.8980+03	.4933+02	.3233-01	.9472+02
25	17	.6707+02	.4749-01	.1009+03	.4915+05	.9646+03	.4927+02	.3484-01	.1041+03
26	17	.6722+02	.5168-01	.1007+03	.4801+05	.9639+03	.4938+02	.3792-01	.1015+03

FIGURE 2-10. POWER LOAD PROFILE ANALYSIS (Sheet 1 of 2)

5040-27

WEEK INDEX	NO. OF MODE REVERSALS	SOLAR OCCULTATION (HOURS)	•••••• WEEKLY DURATION OF •••••• CHARGING PERIODS (HOURS)	SHARE-MODE OPERATIONS (HOURS)	WEEKLY TOTAL OF SOLAR INSOLATION (WT-HRS/SQ.M)	WEEKLY SOLAR INSOLATION MAXIMUM (WATTS/SQ.M)	BATTERY DISCHARGE ENERGY DURING SOLAR OCCULTATION (WATT-HOURS)	SHARE-MODE OPERATIONS (WATT-HOURS)	CHARGING PERIODS (WATT-HOURS)
27	14	.6762+02	.1003+03	.4507-01	.4495+05	.8961+03	.4967+02	.3307-01	.9441+02
28	14	.6824+02	.9970+02	.4799-01	.4875+05	.9620+03	.5013+02	.3520-01	.1020+03
29	14	.6908+02	.9886+02	.5155-01	.4718+05	.9606+03	.5075+02	.3782-01	.9781+02
30	14	.7010+02	.9785+02	.4436-01	.4379+05	.8919+03	.5150+02	.3255-01	.8961+02
31	14	.7126+02	.9668+02	.4666-01	.4699+05	.9556+03	.5225+02	.3423-01	.9526+02
32	14	.7253+02	.9541+02	.4961-01	.4500+05	.9513+03	.5328+02	.3690-01	.8989+02
33	14	.7385+02	.9410+02	.4237-01	.4133+05	.8794+03	.5425+02	.310+01	.8115+02
34	14	.7519+02	.9275+02	.4418-01	.4386+05	.9366+03	.5524+02	.3256-01	.8507+02
35	14	.7653+02	.9142+02	.4716-01	.4152+05	.9253+03	.5622+02	.3461-01	.7921+02
36	14	.7782+02	.9013+02	.4041-01	.3781+05	.8477+03	.5717+02	.2965-01	.7083+02
37	14	.7907+02	.8887+02	.4259-01	.3902+05	.8937+03	.5809+02	.3125-01	.7217+02
38	14	.8028+02	.8766+02	.4565-01	.3570+05	.8734+03	.5898+02	.3350-01	.6488+02
39	14	.8145+02	.8649+02	.3954-01	.3336+05	.7914+03	.5984+02	.2901-01	.5962+02
40	14	.8260+02	.8534+02	.4217-01	.3351+05	.8254+03	.6068+02	.309+01	.5911+02
41	14	.8371+02	.8418+02	.4540-01	.2950+05	.7989+03	.6152+02	.3362-01	.5097+02
42	14	.8491+02	.8301+02	.4021-01	.2880+05	.7177+03	.6238+02	.2951-01	.4900+02
43	14	.8611+02	.8179+02	.4348-01	.2616+05	.6550+03	.6326+02	.3191-01	.4359+02
44	14	.8737+02	.8051+02	.4787-01	.2317+05	.6306+03	.6418+02	.3513-01	.3767+02
45	14	.8869+02	.7919+02	.4256-01	.2471+05	.6068+03	.6516+02	.3124-01	.3971+02
46	14	.9008+02	.7780+02	.4657-01	.2207+05	.5842+03	.6617+02	.3418-01	.3455+02
47	14	.9151+02	.7637+02	.5176-01	.1960+05	.5632+03	.6722+02	.3795-01	.2982+02
48	14	.9296+02	.7491+02	.4633-01	.2106+05	.5444+03	.6829+02	.3400-01	.3163+02
49	14	.9439+02	.7352+02	.5079-01	.1903+05	.5285+03	.6934+02	.3728-01	.2780+02
50	14	.9574+02	.7217+02	.5626-01	.1722+05	.5161+03	.7033+02	.4129-01	.2445+02
51	14	.9694+02	.7098+02	.4984-01	.1898+05	.5079+03	.7122+02	.3657-01	.2676+02
52	14	.9794+02	.6999+02	.5369-01	.1773+05	.5045+03	.7195+02	.3941-01	.2448+02

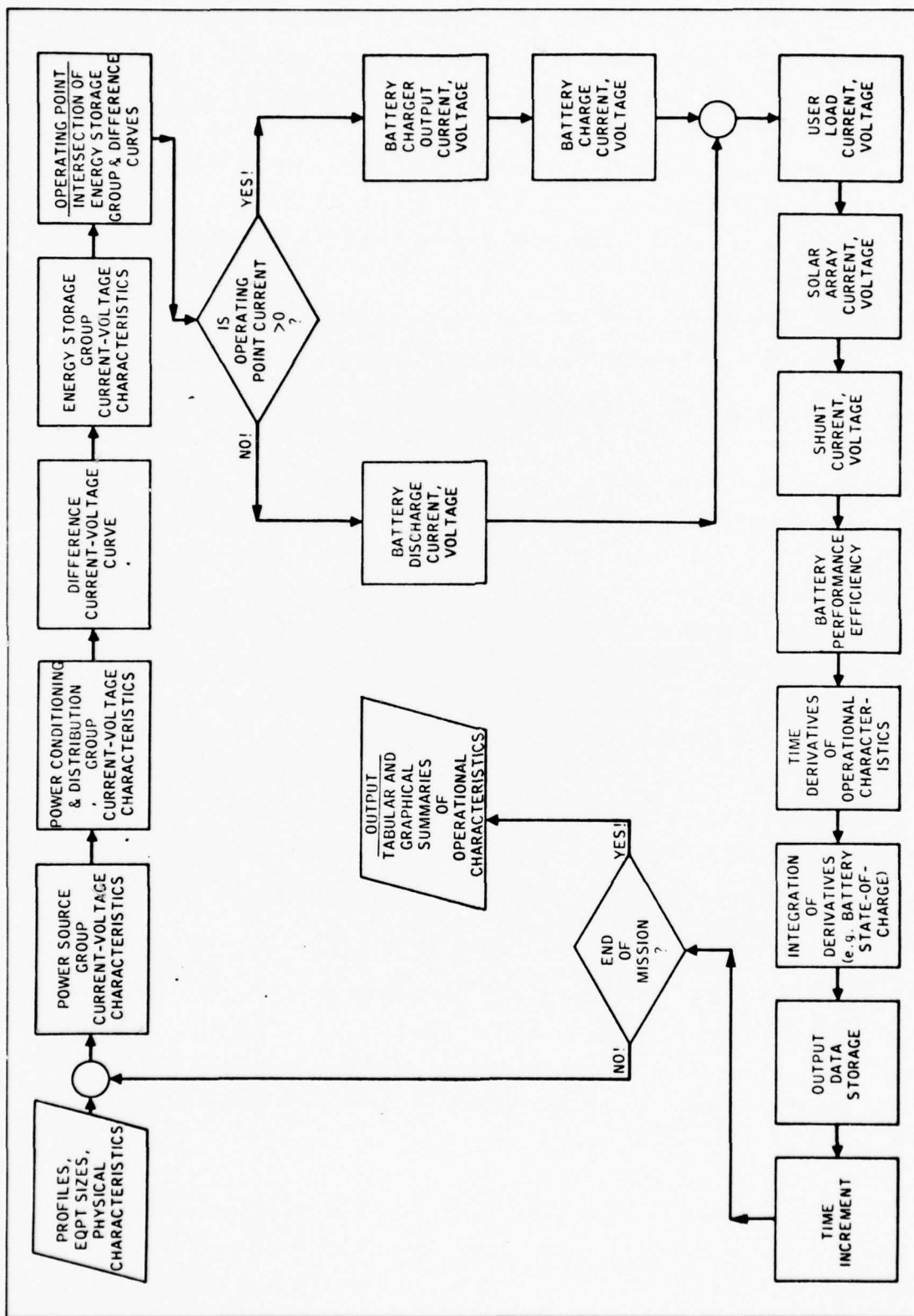FIGURE 2-10. POWER LOAD PROFILE ANALYSIS (Sheet 2 of 2)

FIGURE 2-11. POWER SYSTEM PERFORMANCE ANALYSIS

The performance analysis methodology uses a graphical analysis method, implemented for the computer to obtain the power system operating point for each selected time increment during a mission.

Once this operating point is obtained, all power system operational characteristics are easily determinable. To obtain the operating point, the power system is divided into groups about the operating point (supra). These groups are:

- Power Source Group (PSG).

- Energy Storage Group (ESG).

- Power Conditioning and Distribution Group (PCDG).

Current-voltage (I-V) characteristics of each equipment group are determined. The Power Conditioning and Distribution Group characteristics are then deducted from those of the Power Source Group to obtain a Difference Curve. The intersection of the Difference Curve with the Energy Storage Group characteristics (as determined by the computer program) is an estimate of the voltage and current on the raw power bus (operating point). During the time increment under examination, the battery is in a state of charge, discharge or open-circuit, depending on the value and sign of the operating point current. After the operating point is obtained, the operational characteristics of the power system equipment are determined. The computer program is then ready for examination of power system response for the next time increment. The process is repeated until the end of the mission of interest.

Power Source Group characteristics are determined as shown in Figure 2-12. As a starting point, solar array characteristics are obtained. These characteristics are based on the analytical procedures developed for the JPL Planetary Spacecraft Power Systems Program modified and incorporated into the DSPA computer program.

A major parameter needed in determining solar array characteristics is the level of solar insolation. Solar insolation may be obtained directly from a "MERGE" tape (supra) or estimated by the DSPA computer program.
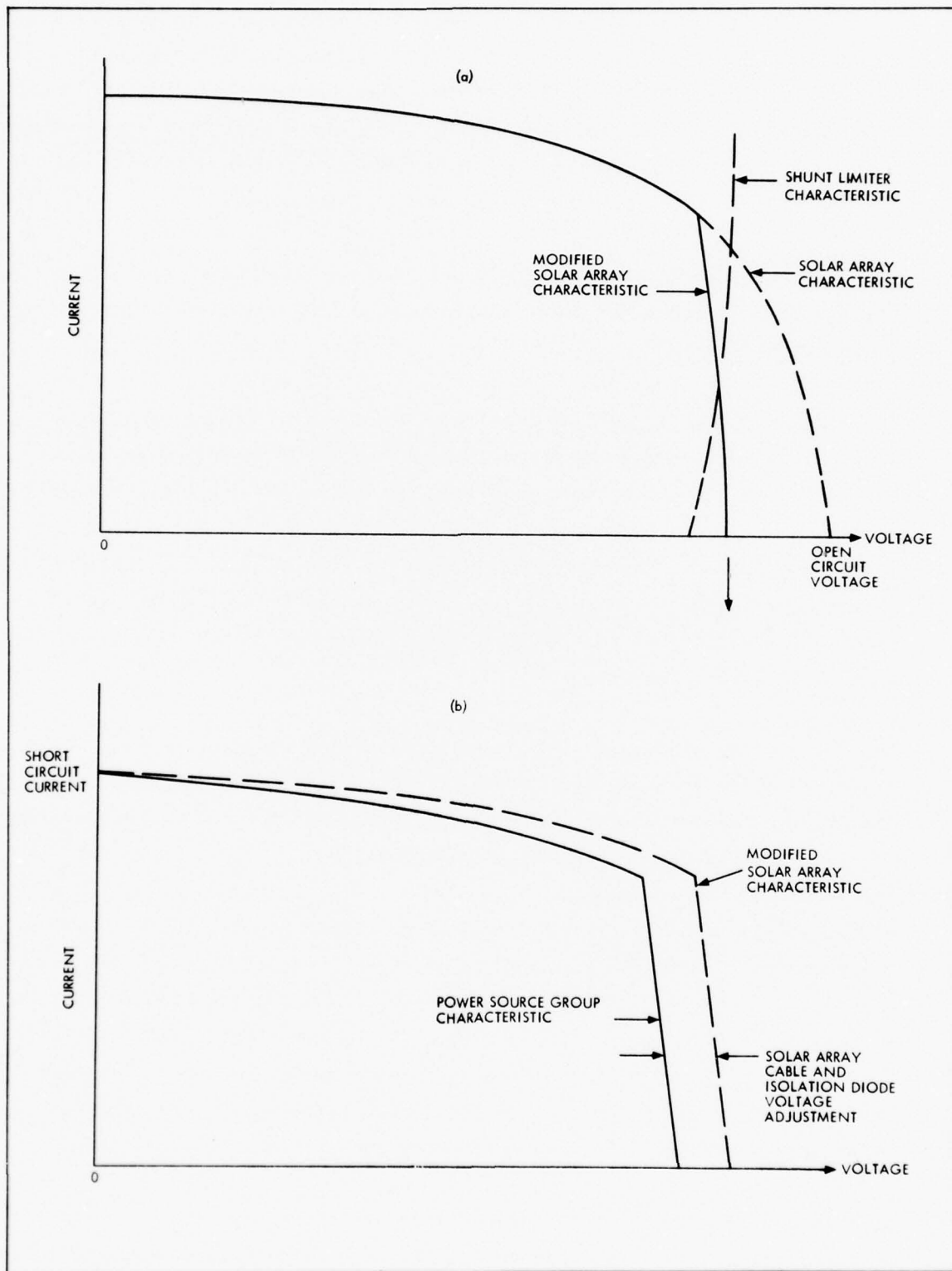
FIGURE 2-12. POWER SOURCE GROUP CHARACTERISTICS

The methodology used in making solar insolation estimates is discussed in Appendix B. The techniques were based upon formulations and algorithms developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (Reference 4). Solar array characteristics are further determined by single solar cell characteristics and degradation as well as the series - parallel arrangement of cells in each module.

Shunt Limiter characteristics are determined by the type of Limiter selected, the desired raw power bus voltage cutoff and the limiter temperature.

The modified solar array characteristic, as shown in Figure 2-12a is obtained by subtracting the shunt limiter current from the solar array current at each point between zero volts and array open circuit voltage.

Power Source Group characteristics, shown in Figure 2-12b, are obtained by subtracting the isolation diode and cable voltage drops from the modified solar array voltage at each point between zero amperes and modified solar array short circuit current.

The methodology of determining Power Conditioning and Distribution Group characteristics is discussed in Appendix C. Using these characteristics, the interaction between the Power Source Group and the Power Conditioning and Distribution Group is shown in Figure 2-13.

A load line difference curve is used to determine the interaction of the Power Source, Energy Storage and PC&D Groups. The difference curve, as indicated in Figure 2-13b, is obtained by subtracting the PC&D Group current from the Power Source Group current at each voltage level. By operating along positive values of the difference curve, the solar array has excess power which can be used to charge the batteries. Operating on negative values of the difference curve will result in battery discharge.

Techniques for estimating the current-voltage characteristics of the Energy Storage Group are given in Appendix D. Using these characteristics, the interaction between the Energy Storage Group and the Load Difference
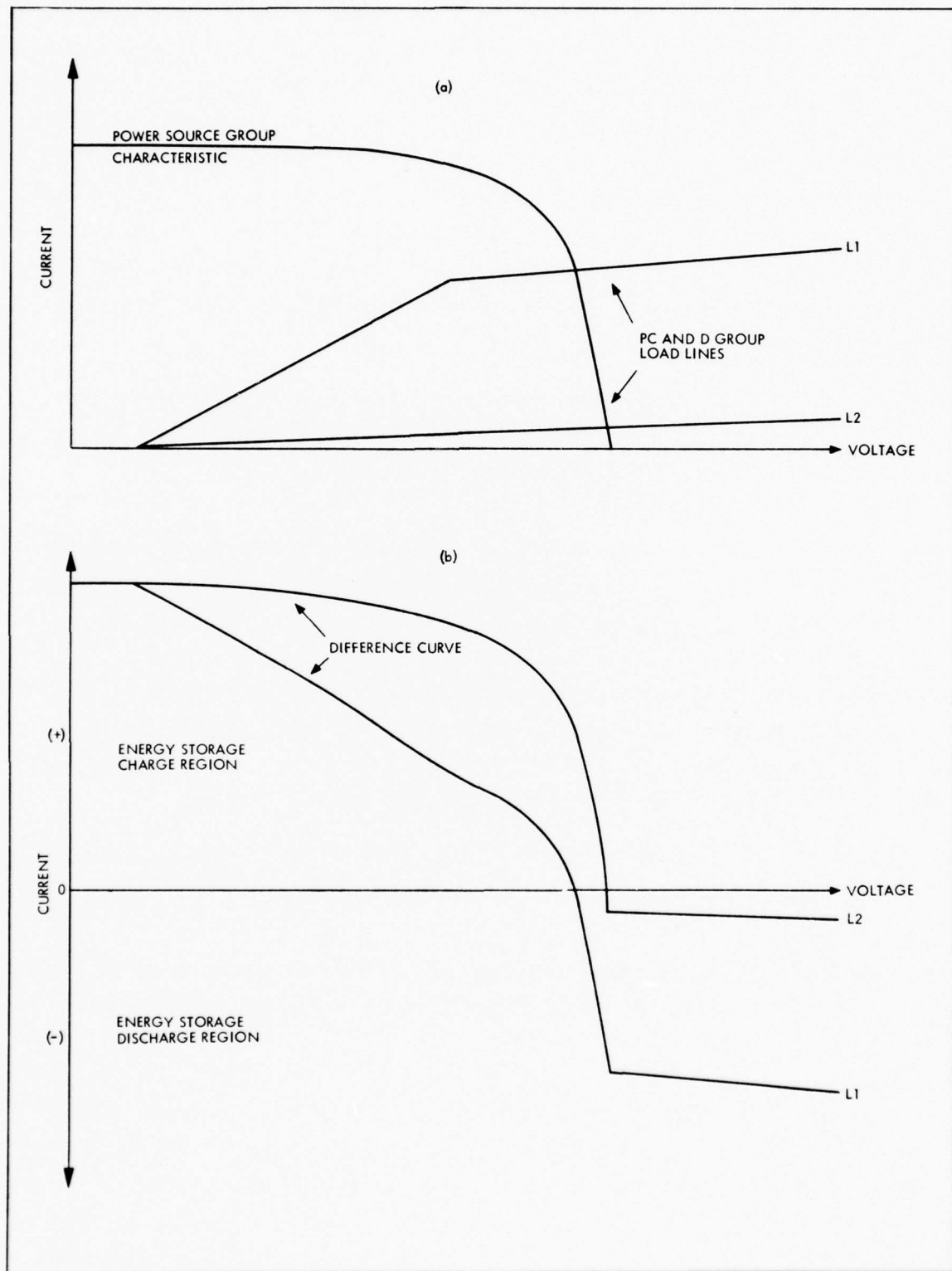
FIGURE 2-13.   LOAD LINE DIFFERENCE

Curve during Load Line Analysis is shown in Figure 2-14. Load Line Analysis is performed by determining the point of intersection (power system operating point) of the Energy Storage Group Characteristic with the Load Difference Curve.

The interactions in Figure 2-14 also indicate the change in power system operation with battery state of charge. These several operating points include:

- Battery Charging - (Operating Points 1D, 2D).

- Battery Floating - (Operating Point 3D).

- Share Mode (Battery Discharging and sharing load with Solar Array) - (Operating Point 4D).

- Battery Discharge - (Operating Points 5D, 6D, IN-6N).

The major elements (subroutines) of the performance analysis subprogram are shown in Figure 2-15. Functions performed by each of the major subroutines are also shown in this figure.

Examples of tabular output from performance analysis calculations are shown in Figures 2-16 to 2-18. This output includes separate tabular presentations for:

- Unregulated Bus Summary Data.

- Power Source Group Summary Data.

- Energy Storage Unit Summary Data.

These tabulation show the predicted performance of the major power system elements for selected time increments over a selected period of the mission.

One form of graphical output is shown in Figures 2-19 to 2-21. These forms of output illustrate the factors involved in load line analysis for selected times during the mission. The particular times shown in these figures are at 4:00 a.m., 8:00 a.m. and 12:00 noon on January 1, 1975.

FIGURE 2-14. LOAD LINE ANALYSIS

PADRVR	MAIN PERFORMANCE ANALYSIS DRIVER PROGRAM
PA-BATEFC	COMPUTES BATTERY EFFICIENCY
PA-CRVPLT	GENERATES "INSTANTANEOUS" I-V PLOTS
PA-ESGC	COMPUTES ENERGY STORAGE GROUP I-V CHARACTERISTICS
PA-ESGIV	COMPUTES BATTERY CURRENT AND VOLTAGE CHARACTERISTICS
PA-INTER	COMPUTES OPERATING POINT CURRENT AND VOLTAGE
PA-PCDGC	COMPUTES POWER CONDITIONING AND DISTRIBUTION GROUP CURRENT AND VOLTAGE CHARACTERISTICS
PA-PSGC	COMPUTES POWER SOURCE GROUP I-V CHARACTERISTICS
PA-SLIVC	COMPUTES SHUNTER LIMITER I-V CHARACTERISTICS
PA-PRTPLT	GENERATES OUTPUT PLOTS AND TABLES

FIGURE 2-15.   PERFORMANCE ANALYSIS SUBPROGRAM ELEMENTS

The second form of graphical output is shown in Figures 2-22 and 2-23.
This output includes separate graphical illustrations of:

- Power Source Group Summary Plots.

- Battery Performance Summary Plots.

These illustrations show the temporal trends in selected data taken from
the tabular presentations (Figures 2-11 to 2-18) discussed above. In
particular, the information in Figure 2-23 shows that available battery
capacity (a critical performance parameter) appears to be holding steady
(for the design represented by these curves) during the low solar insola-
tion winter days.

NAVIGATION AID POWER SYSTEM PERFORMANCE ANALYSIS

TABLE 1: UNREGULATED BUS SUMMARY

DATE OF TEST YEAR:DAY:HOUR	TIME SINCE START (DAYS)	POWER SYSTEM OPERATING VOLTAGE (VOLTS)	POWER SOURCE GROUP POWER (WATTS)	POWER SOURCE GROUP CURRENT (AMPERES)	ENERGY STORAGE GROUP POWER (WATTS)	ENERGY STORAGE GROUP CURRENT (AMPERES)	POWER CONDITIONING AND DISTRIBUTION GROUP POWER (WATTS)	POWER CONDITIONING AND DISTRIBUTION GROUP CURRENT (AMPERES)
1975: 1: .00	.00	10.33	.0000	.0000	.5575+00	-.5398-01	.5575+00	.5398-01
1975: 1: 4.00	.17	10.31	.0000	.0000	.5556+00	-.5388-01	.5556+00	.5388-01
1975: 1: 8.00	.33	11.70	.1208+01	.1032+00	.1164+01	.9948-01	.4399-01	.3761-02
1975: 1:12.00	.50	12.25	.1371+02	.1120+01	.1367+02	.1116+01	.4649-01	.3796-02
1975: 1:16.00	.67	11.68	.1711+01	.1465+00	.1667+01	.1427+00	.4392-01	.3760-02
1975: 1:20.00	.83	10.21	.0000	.0000	.5450+00	-.5337-01	.5450+00	.5337-01
1975: 2: 4.00	1.17	10.33	.0000	.0000	.5572+00	-.5397-01	.5572+00	.5397-01
1975: 2: 8.00	1.33	11.72	.1204+01	.1027+00	.1160+01	.9898-01	.4409-01	.3762-02
1975: 2:12.00	1.50	11.97	.7890+01	.6590+00	.7845+01	.6553+00	.4524-01	.3779-02
1975: 2:16.00	1.67	11.64	.8906+00	.7649-01	.8463+00	.7274-01	.4374-01	.3757-02
1975: 2:20.00	1.83	10.22	.0000	.0000	.5455+00	-.5339-01	.5455+00	.5339-01
1975: 3: 4.00	2.17	10.33	.0000	.0000	.5576+00	-.5398-01	.5576+00	.5394-01
1975: 3: 8.00	2.33	11.72	.1194+01	.1018+00	.1150+01	.9807-01	.4411-01	.3762-02
1975: 3:12.00	2.50	11.99	.8025+01	.6696+00	.7980+01	.6658+00	.4530-01	.3779-02
1975: 3:16.00	2.67	11.65	.9390+00	.8061-01	.8952+00	.7605-01	.4377-01	.3758-02
1975: 3:20.00	2.83	10.22	.0000	.0000	.5459+00	-.5341-01	.5459+00	.5341-01
1975: 3:24.00	3.00	10.28	.0000	.0000	.5520+00	-.5371-01	.5520+00	.5371-01

FIGURE 2-16. UNREGULATED BUS SUMMARY DATA

NAVIGATION AID POWER SYSTEM PERFORMANCE ANALYSIS

TABLE 21 POWER SOURCE GROUP SUMMARY

DATE OF TEST YEAR:DAY:HOUR	TIME SINCE START (DAYS)	POWER SOURCE GROUP TEMP. (DEG. F)	INCIDENT SOLAR RADIATION (WATTS/SQ.M)	SOLAR ARRAY VOLTAGE (VOLTS)	CURRENT (AMPERES)	POWER (WATTS)	MAXIMUM POWER (WATTS)	POWER MARGIN (WATTS)	SHUNT LIMITER VOLTAGE (VOLTS)	CURRENT (AMPERES)	POWER (WATTS)
1975: 1: .00	.00	63.54	.0000	.0000	.0000	.0000	.0000	.0000	.1033+02	.0000	.0000
1975: 1: 4.00	.17	64.26	.0000	.0000	.0000	.0000	.0000	.0000	.1031+02	.0000	.0000
1975: 1: 8.00	.33	75.96	.6656+02	.1230+02	.1032+00	.1270+01	.1285+01	.1513-01	.1170+02	.0000	.0000
1975: 1:12.00	.50	62.26	.5735+03	.1209+02	.1120+01	.1455+02	.1455+02	.1311-05	.1225+02	.0000	.0000
1975: 1:16.00	.67	80.46	.8965+02	.1229+02	.1465+00	.1801+01	.1843+01	.4226-01	.1158+02	.0000	.0000
1975: 1:20.00	.83	71.46	.0000	.0000	.0000	.0000	.0000	.0000	.1021+02	.0000	.0000
1975: 2: 4.00	1.17	64.28	.0000	.0000	.0000	.0000	.0000	.0000	.1033+02	.0000	.0000
1975: 2: 8.00	1.33	75.98	.6656+02	.1232+02	.1027+00	.1246+01	.1249+01	.1987-01	.1172+02	.0000	.0000
1975: 2:12.00	1.50	62.28	.3747+03	.1267+02	.659+00	.8351+01	.8357+01	.6579-02	.1197+02	.0000	.0000
1975: 2:16.00	1.67	80.48	.5516+02	.1274+02	.7649-01	.9362+00	.1004+01	.6760-01	.1144+02	.0000	.0000
1975: 2:20.00	1.83	71.48	.0000	.0000	.0000	.0000	.0000	.0000	.1022+02	.0000	.0000
1975: 3: 4.00	2.17	64.30	.0000	.0000	.0000	.0000	.0000	.0000	.1033+02	.0000	.0000
1975: 3: 8.00	2.33	76.00	.6618+02	.1233+02	.1016+00	.1256+01	.1275+01	.20.7-01	.1172+02	.0000	.0000
1975: 3:12.00	2.50	82.30	.3702+03	.1269+02	.6696+00	.6494+01	.6594+01	.4154-02	.1199+02	.0000	.0000
1975: 3:16.00	2.67	80.50	.5727+02	.1225+02	.8061-01	.9787+00	.1050+01	.6245-01	.1165+02	.0000	.0000
1975: 3:20.00	2.83	71.50	.0000	.0000	.0000	.0000	.0000	.0000	.1022+02	.0000	.0000
1975: 3:24.00	3.00	67.90	.0000	.0000	.0000	.0000	.0000	.0000	.1028+02	.0000	.0000

FIGURE 2-17. POWER SOURCE GROUP SUMMARY DATA

NAVIGATION AID POWER SYSTEM PERFORMANCE ANALYSIS

TABLE 031 ENERGY STORAGE UNIT SUMMARY, 2 BATTERIES

DATE OF TEST YEAR:DAY:HOUR	TIME SINCE START (DAYS)	ENERGY STORAGE GROUP TEMP. (DEG. F)	ENERGY STORAGE UNIT POWER (WATTS)	VOLTAGE (VOLTS)	BATTERY POWER (WATTS)	CURRENT (AMPERES)	VOLTAGE (VOLTS)	STATE OF CHARGE	CAPACITY (AMP-HOURS)	SPECIFIC GRAVITY	FREEZING TEMP. (DEG. F)
1975: 1: .00	.00	58.54	.2802+00	.1033+02	.2797+00	-.2702-01	.1035+02	.7500+00	.1500+02	.1247+01	-.6134+02
1975: 1: 4.00	.17	59.26	.2794+00	.1031+02	.2788+00	-.2699-01	.1033+02	.7446+00	.1489+02	.1246+01	-.6000+02
1975: 1: 8.00	.33	70.96	.5816+00	.1170+02	.5045+00	.4972-01	.1015+02	.7411+00	.1482+02	.1245+01	-.5914+02
1975: 1:12.00	.50	77.26	.6833+01	.1225+02	.5678+01	.5579+00	.1018+02	.7747+00	.1549+02	.1253+01	-.6744+02
1975: 1:16.00	.67	75.46	.8331+00	.1168+02	.7209+00	.7131-01	.1011+02	.7843+00	.1577+02	.1255+01	-.7000+02
1975: 1:20.00	.83	66.46	.2741+00	.1021+02	.2735+00	-.2673-01	.1023+02	.7836+00	.1547+02	.1254+01	-.6764+02
1975: 2: 8.00	1.17	59.28	.2803+00	.1033+02	.2797+00	-.2703-01	.1035+02	.7727+00	.1545+02	.1257+01	-.6976+02
1975: 2:12.00	1.33	70.98	.5795+00	.1172+02	.5028+00	.4945-01	.1017+02	.7692+00	.1538+02	.1251+01	-.6610+02
1975: 2:16.00	1.50	77.28	.3922+01	.1197+02	.3322+01	.3276+00	.1014+02	.7891+00	.1576+02	.1256+01	-.7101+02
1975: 2:20.00	1.67	75.48	.4229+00	.1164+02	.3671+00	.3632-01	.1011+02	.7970+00	.1594+02	.1257+01	-.7296+02
1975: 3: .00	1.83	66.48	.2743+00	.1022+02	.2737+00	-.2674-01	.1024+02	.7923+00	.1585+02	.1254+01	-.7181+02
1975: 3: 4.00	2.17	59.10	.2804+00	.1033+02	.2799+00	-.2704-01	.1035+02	.7815+00	.1563+02	.1254+01	-.6913+02
1975: 3: 8.00	2.33	71.00	.5743+00	.1172+02	.4984+00	.4889-01	.1017+02	.7780+00	.1556+02	.1253+01	-.6826+02
1975: 3:12.00	2.50	77.30	.3989+01	.1199+02	.3377+01	.3328+00	.1015+02	.7981+00	.1596+02	.1258+01	-.7323+02
1975: 3:16.00	2.67	75.50	.4470+00	.1165+02	.3980+00	.3838-01	.1011+02	.8061+00	.1612+02	.1259+01	-.7518+02
1975: 3:20.00	2.83	64.50	.2743+00	.1022+02	.2737+00	-.2473-01	.1024+02	.8014+00	.1603+02	.1258+01	-.7404+02
1975: 3:24.00	3.00	62.90	.2774+00	.1028+02	.2768+00	-.2688-01	.1030+02	.7960+00	.1592+02	.1257+01	-.7272+02

FIGURE 2-18. ENERGY STORAGE UNIT SUMMARY DATA

BEST AVAILABLE COPY
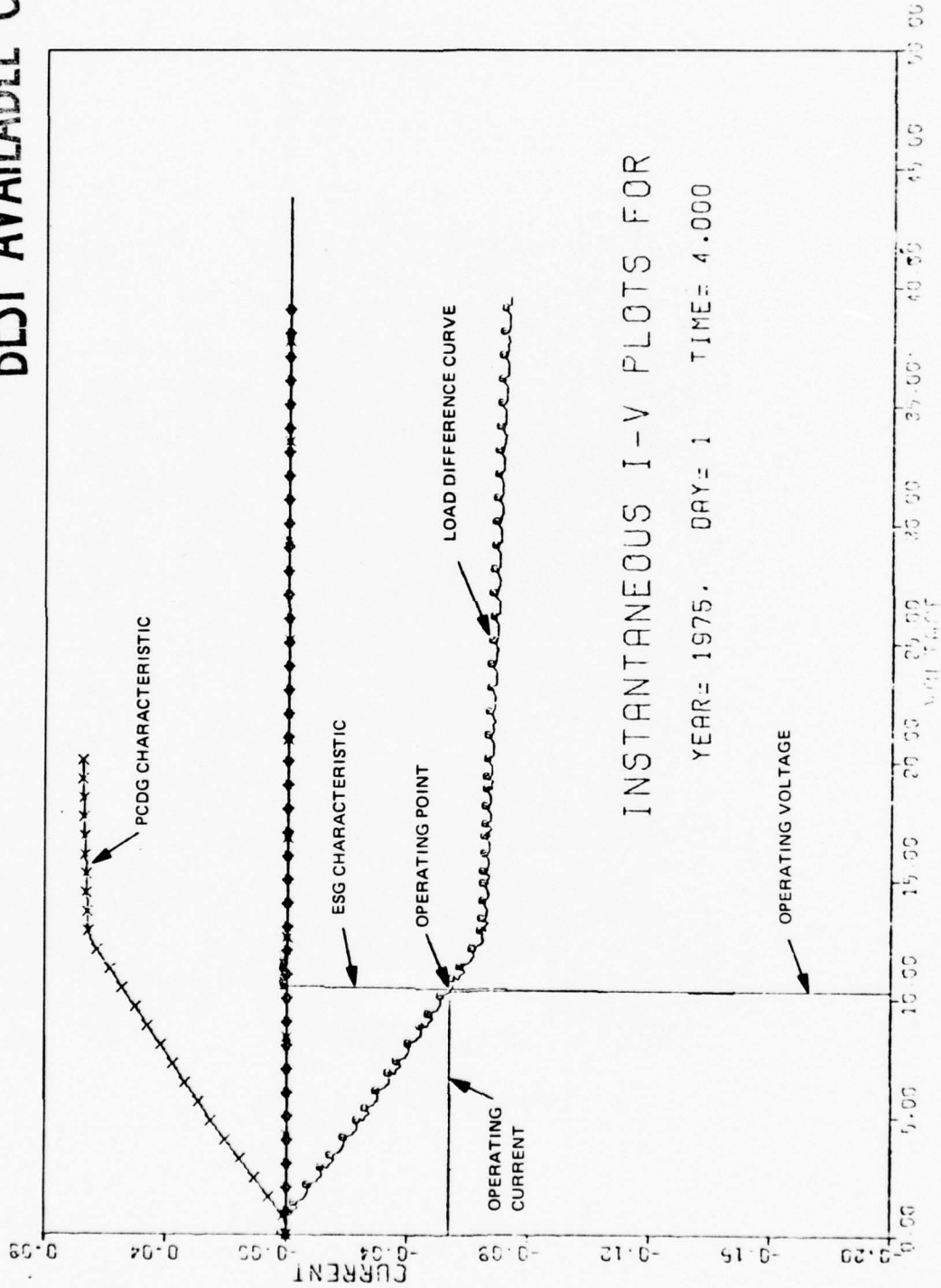
FIGURE 2-19. INSTANTANEOUS CURRENT-VOLTAGE PLOTS

INSTANTANEOUS I-V PLOTS FOR:

YEAR= 1975. DAY= 1. TIME= 8.000

PSG CHARACTERISTIC

LOAD DIFFERENCE CURVE

OPERATING CURRENT

ESG CHARACTERISTIC

OPERATING POINT

PCDG CHARACTERISTIC

OPERATING VOLTAGE

CURRENT

VOLTAGE

FIGURE 2-20. INSTANTANEOUS CURRENT-VOLTAGE PLOTS

FIGURE 2-21.   INSTANTANEOUS CURRENT - VOLTAGE PLOTS

BEST AVAILABLE COPY
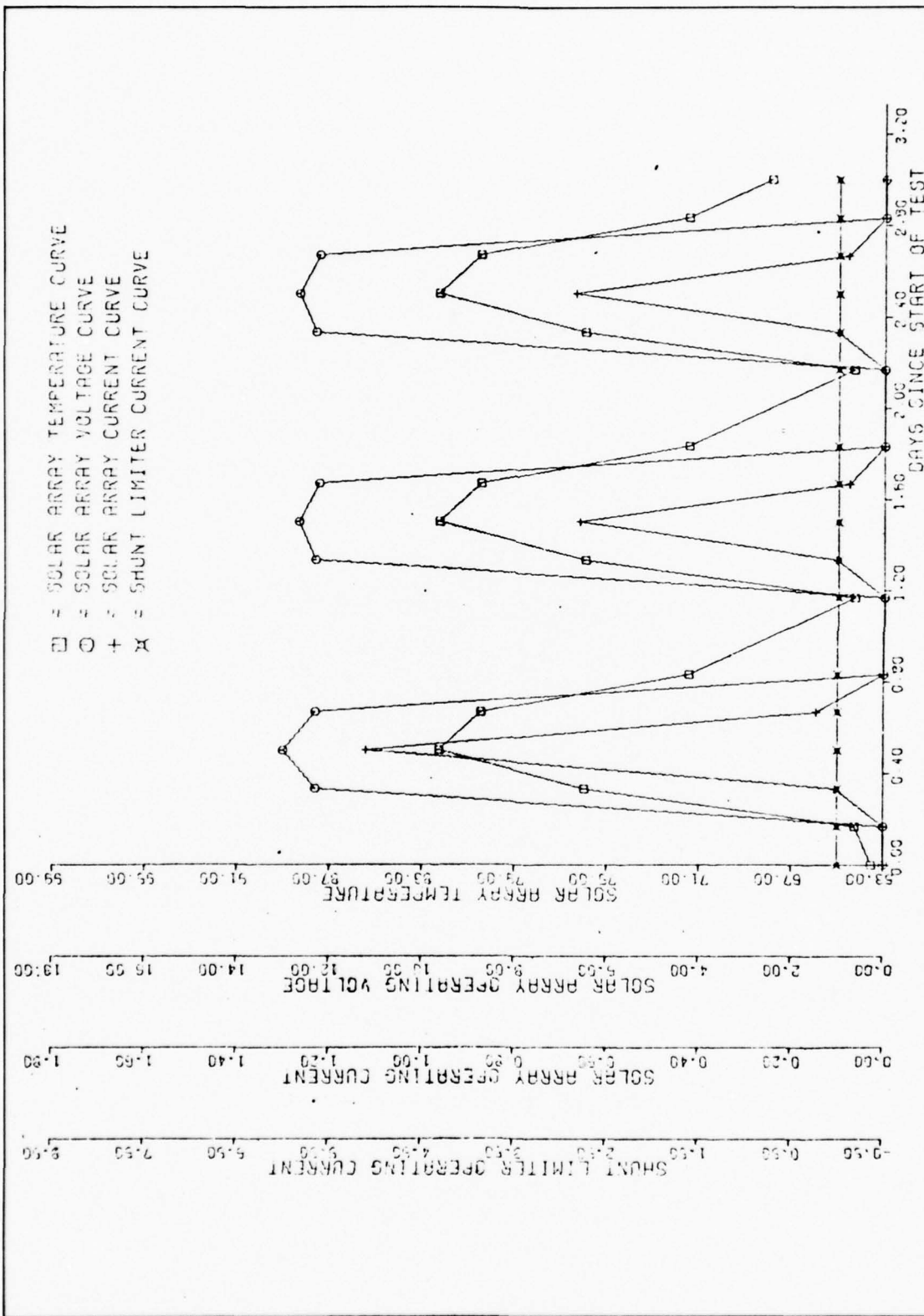
FIGURE 2-22. POWER SOURCE GROUP SUMMARY PLOTS

2-35
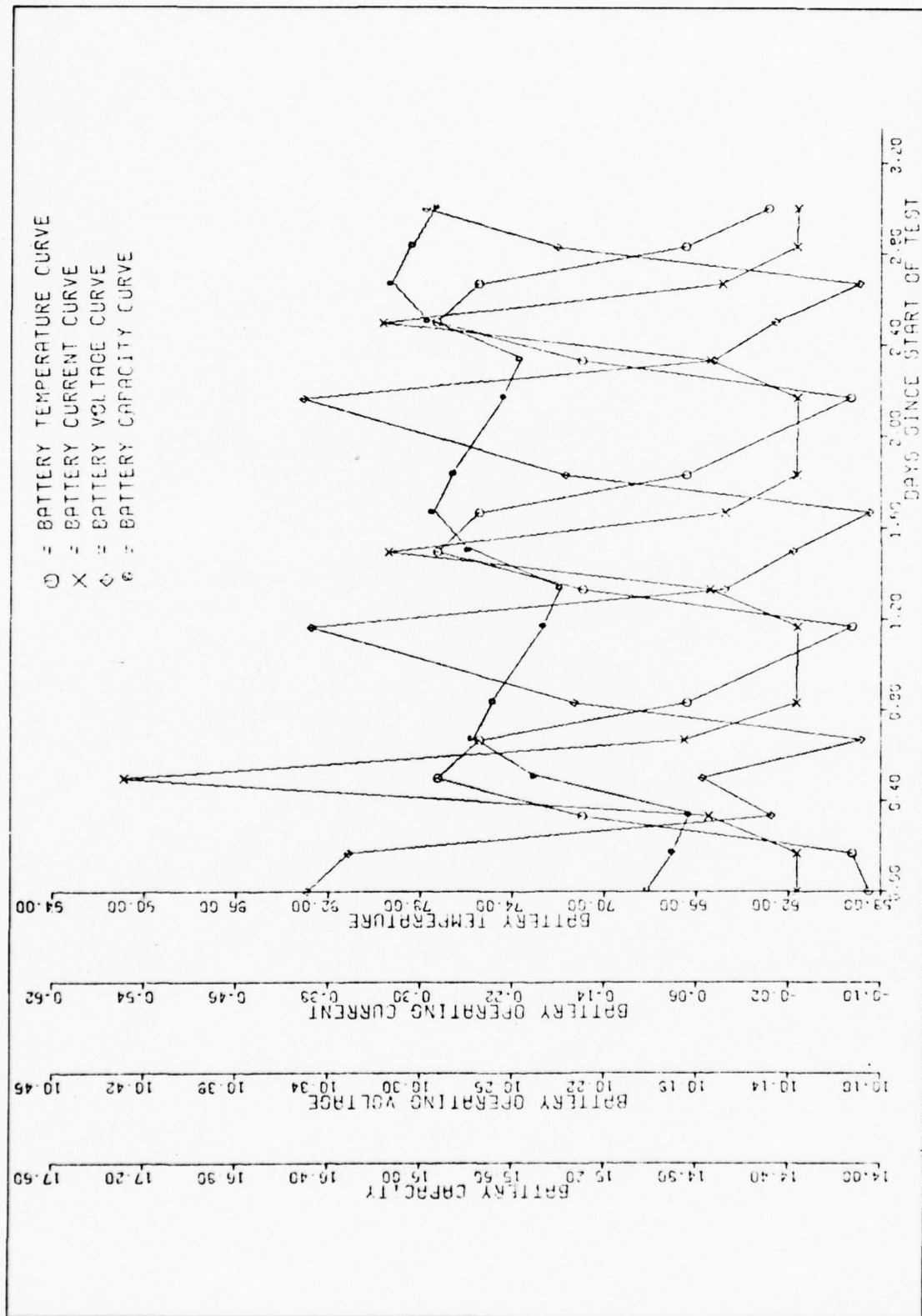
FIGURE 2-23. BATTERY PERFORMANCE SUMMARY PLOTS

3.   PROGRAM DATA

Exact values of all numerical program data may be found in Program Documentation (Volume II, Users Manual). The basis for key elements of this data, however, will be presented in this section of the report.

Program Data may be conveniently placed in three categories corresponding to the three major categories of equipment, i.e.,

- Power Source Group.

- Energy Storage Group.

- Power Conditioning and Distribution Group.

Key data for these equipment groups is discussed below.

3.1 Power Source Group

Information needed in determining Power Source Group performance and characteristics includes estimates of solar insolation. These estimates may be obtained by the methods indicated in Appendix B. This appendix also contains the following data needed in making estimates of solar insolation:

- Time Zones in the United States (Figure B-2).

- Time Zone Numbers in United States for Standard Time (Table B-1).

- Clearness numbers of Nonindustrial Atmosphere in the United States (Figure B-3).

- Solar Radiation Variables (Table B-2).

- Solar Radiation Fourier Coefficients (Table B-3).

- Cloud Cover Modifiers (Table B-4).

- Cloud Cover Modifier Equations (Table B-5).

Another important parameter affecting performance is the solar cell spectral correction factor. Data received from the U.S. Coast Guard (Reference 5) indicate that the short circuit current of a solar cell, above the atmosphere, is related to solar cell short circuit current at the earth's surface by the following:

$$I_{sc} \begin{Bmatrix} 135.6 \text{ mw/cm}^2 \\ \text{AMO} \end{Bmatrix} = (1.146)\ I_{sc} \begin{Bmatrix} 100 \text{ mw/cm}^2 \\ \text{AM1} \end{Bmatrix} \qquad (3-1)$$

where:

$I_{sc} \begin{Bmatrix} 135.6 \text{ mw/cm}^2 \\ \text{AMO} \end{Bmatrix} =$ Solar Cell Short circuit current above the atmosphere (AMO) at a standard solar insolation of 135.6 milliwatts/cm^2

$I_{sc} \begin{Bmatrix} 100 \text{ mw/cm}^2 \\ \text{AM1} \end{Bmatrix} =$ Solar Cell Short circuit current at the earth's surface (AM1) at a standard solar insolation of 100 milliwatts/cm^2

Thus, the spectral correction factor (SPECOR) is:

$$\text{SPECOR} = \left(\frac{135.6}{100}\right)\left(\frac{1}{1.146}\right) = 1.183 \qquad (3-2)$$

Variations in the average daily temperature are typically represented by the yearly temperature profile for Los Angeles, California (Reference 6), shown in Figure 3-1.

Information on the performance of terrestrial solar arrays under test were obtained from the Coast Guard (Reference 7). The data obtained from these tests were used to estimate the equivalent solar cell characteristics for two types of arrays of interest to the Coast Guard. These cell characteristics are shown in Figures 3-2 and 3-3. Extrapolation of cell performance beyond measured data is required because of the DSPA Computer Program methodology used for solar array performance characteristics.

A number of solid-state devices have been used as solar array isolation diodes by the Coast Guard (Reference 7). The characteristics of two of these devices are shown in Figures 3-4 and 3-5. One of these devices is a rectifier diode (Figure 3-4). The other device is a zener diode which was used by the Coast Guard as a rectifier diode because of its low reverse leakage current (at less than zener breakdown voltage - 39 volts).
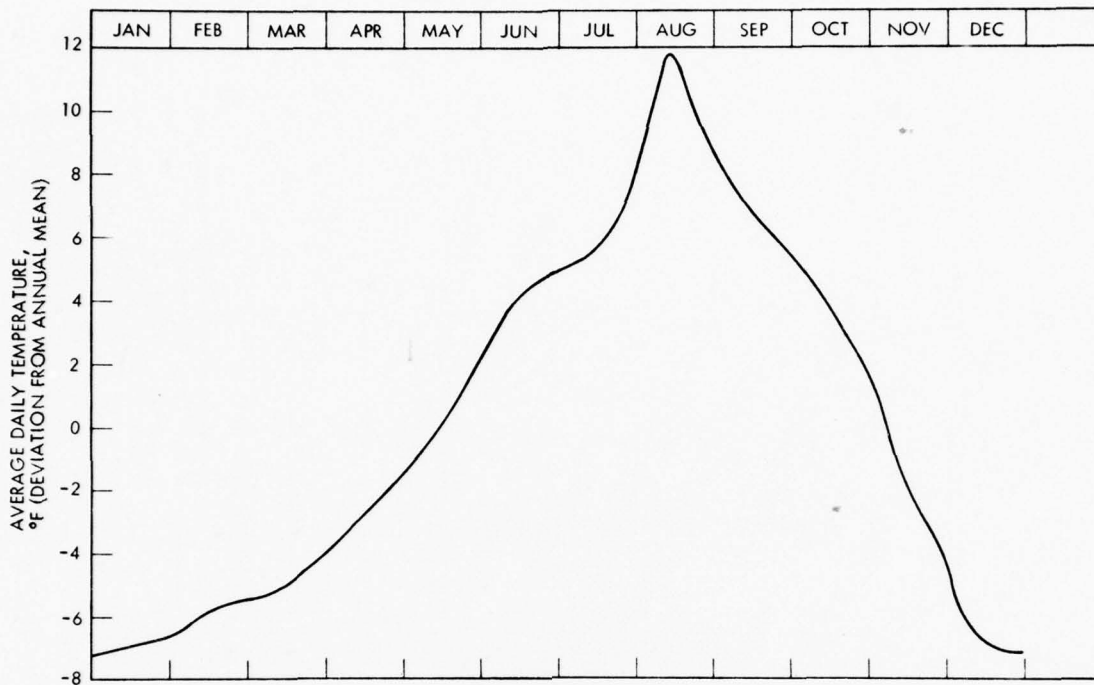
FIGURE 3-1. AVERAGE DAILY TEMPERATURE, LOS ANGELES, CALIF. (ANNUAL MEAN TEMPERATURE = 58.9°F)
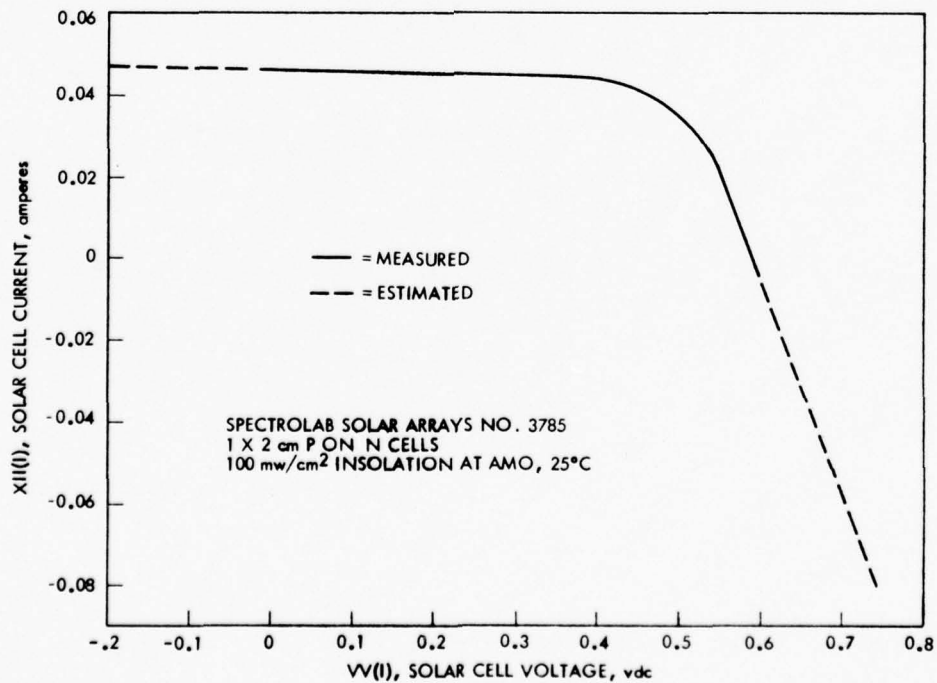
FIGURE 3-2. EQUIVALENT SOLAR-CELL CHARACTERISTICS
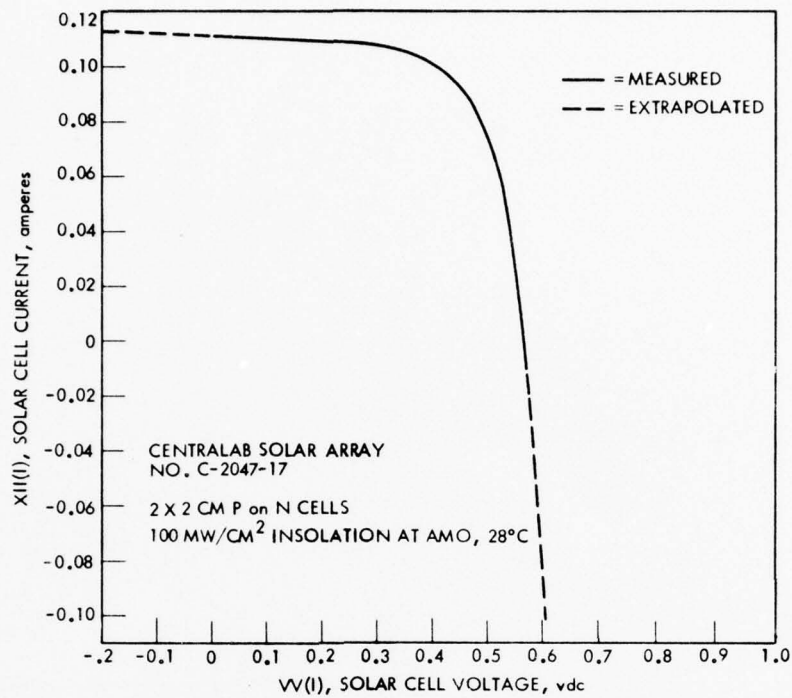
FIGURE 3-3. EQUIVALENT SOLAR CELL CHARACTERISTICS

1N1341A RECTIFIER DIODE
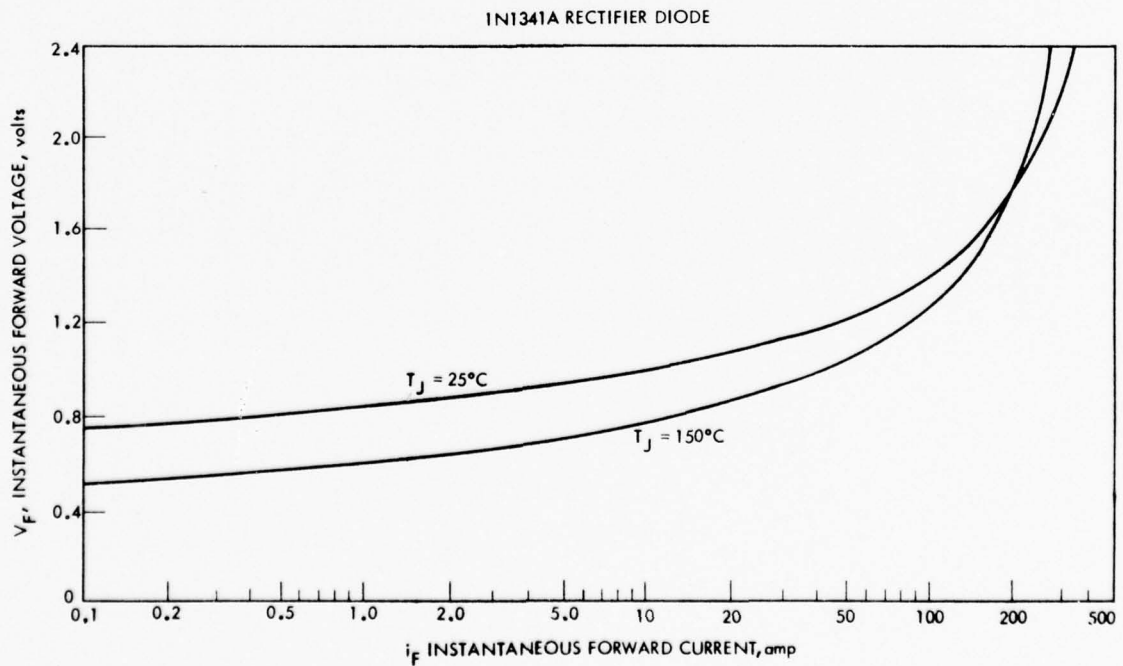
FIGURE 3-4. SOLAR ARRAY ISOLATION DIODE CHARACTERISTICS
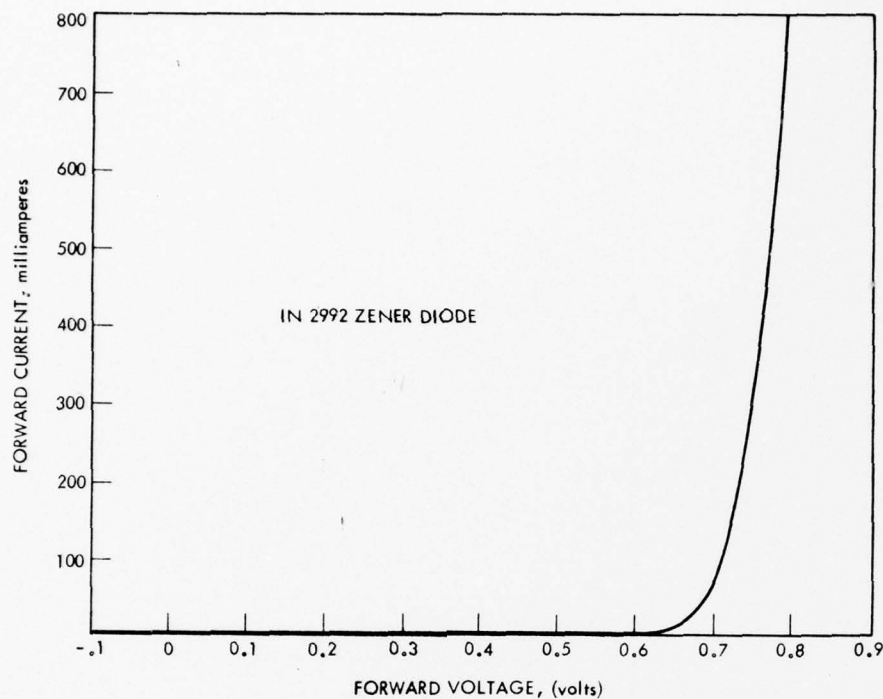
FIGURE 3-5. SOLAR ARRAY ISOLATION DIODE CHARACTERISTICS

Shunt limiters, included in the DSPA Computer program are:

- Ordinary zener diodes.

- Temperature compensated zener diodes.

- Active shunt limiter.

Temperature coefficients for ordinary zener diodes are shown in Figure 3-6 (Reference 8). The information in this figure shows that zener diodes with a breakdown voltage in the vicinity of 5.1 volts have a zero temperature coefficient and may also be considered "temperature-compensated."

The impedance of ordinary zener diodes is shown in Figure 3-7. The data shown in Figures 3-6 and 3-7 are used to estimate the current-voltage characteristics of ordinary zener diodes.

Characteristics of a typical series of temperature-compensated zener diodes, as a function of temperature, are shown in Figure 3-8 (Reference 8).
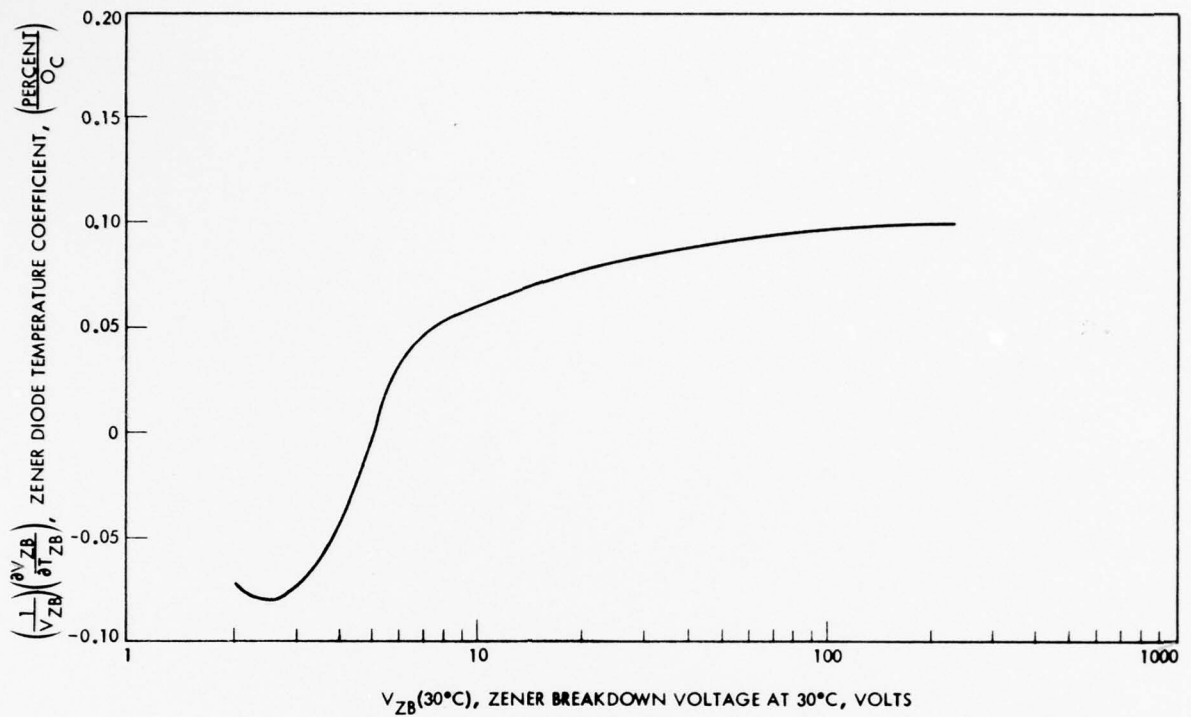
FIGURE 3-6. ZENER DIODE TEMPERATURE COEFFICIENTS
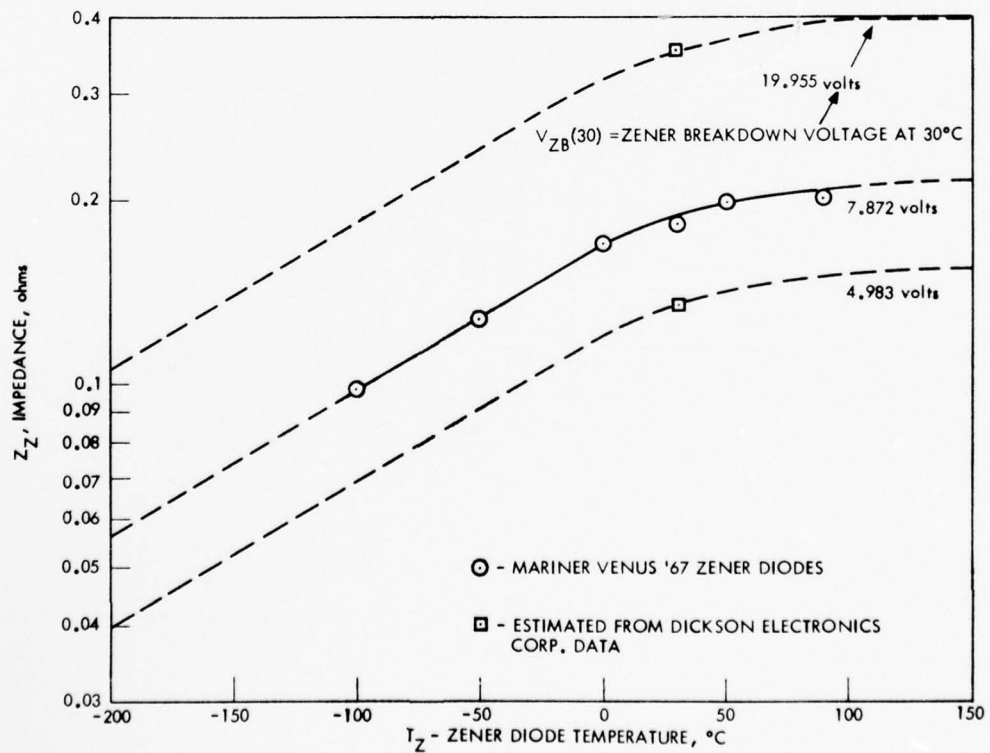
FIGURE 3-7. ZENER DIODE IMPEDANCE
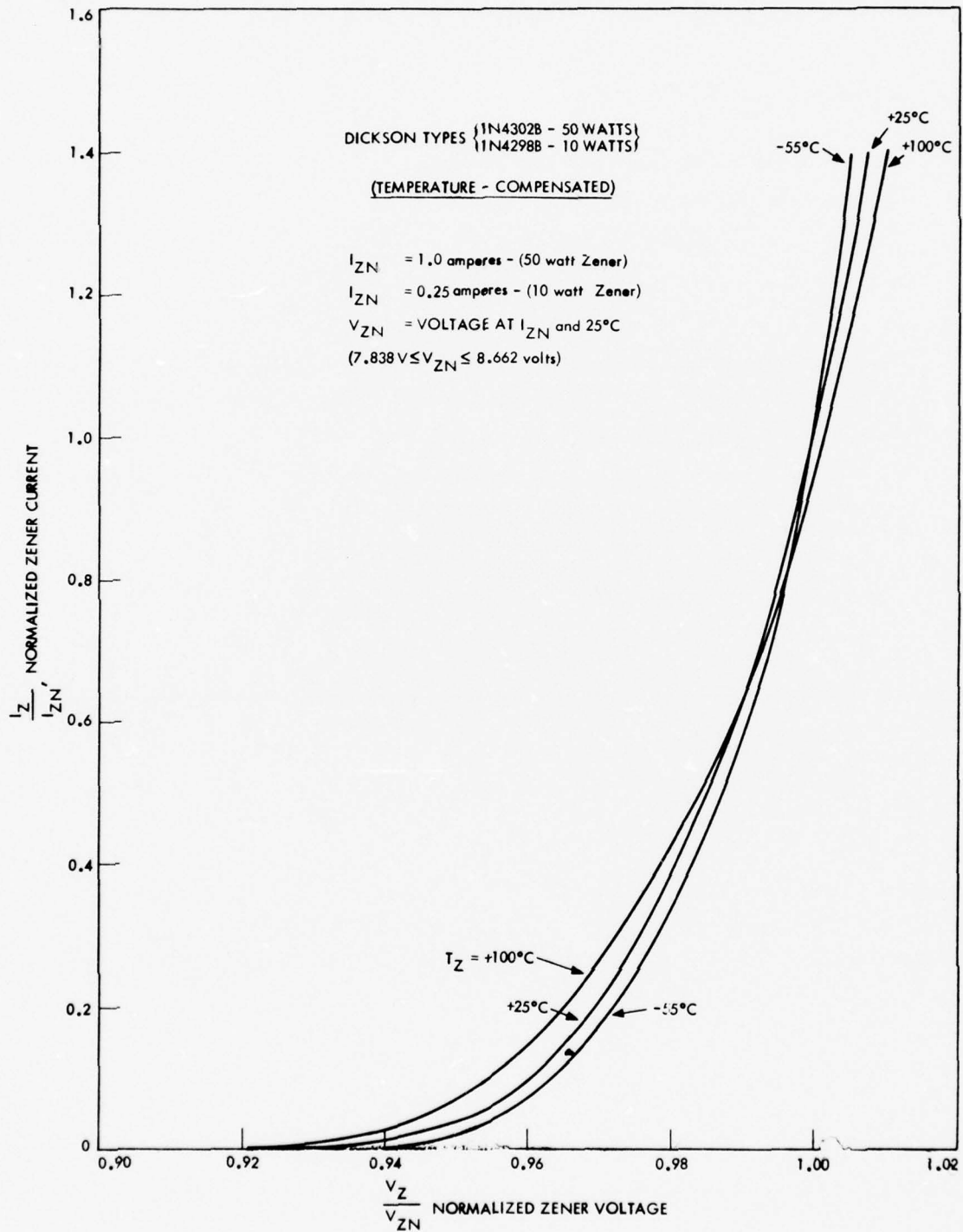
FIGURE 3-8. CURRENT − VOLTAGE CHARACTERISTICS OF ZENER DIODES
(TEMPERATURE-COMPENSATED)

The performance characteristics of an active shunt limiter used by the Coast Guard (Reference 7) are given in Figure 3-9.

3.2 Energy Storage Group

Data have been obtained for two storage cell types of interest to the Coast Guard. The batteries of interest are:

- Lead – Acid Batteries.
- Nickel – Cadmium Batteries.

The effect of temperature and discharge rate on lead-acid battery capacity is shown in Figure 3-10 (References 9-15). As shown in this figure, standard discharge conditions are:

- Normalized Discharge Rate – 0.05 Amperes/Ampere-Hours (20 hour rate).
- Temperature – 20°C.
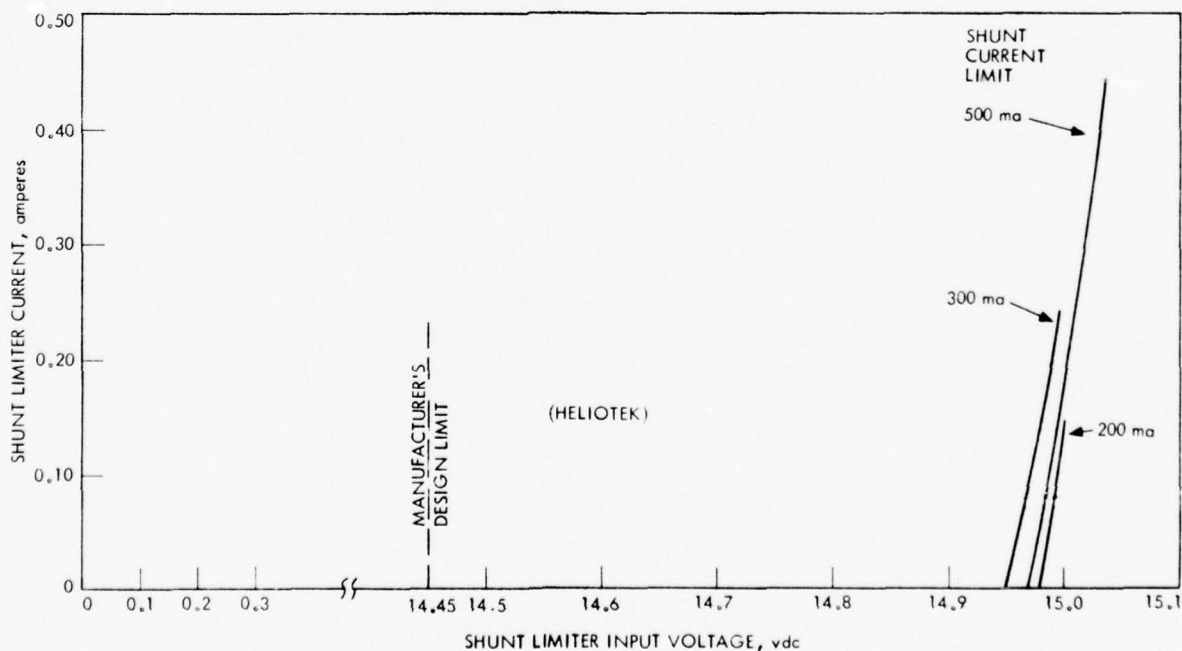
FIGURE 3-9. ACTIVE SHUNT LIMITER CHARACTERISTICS
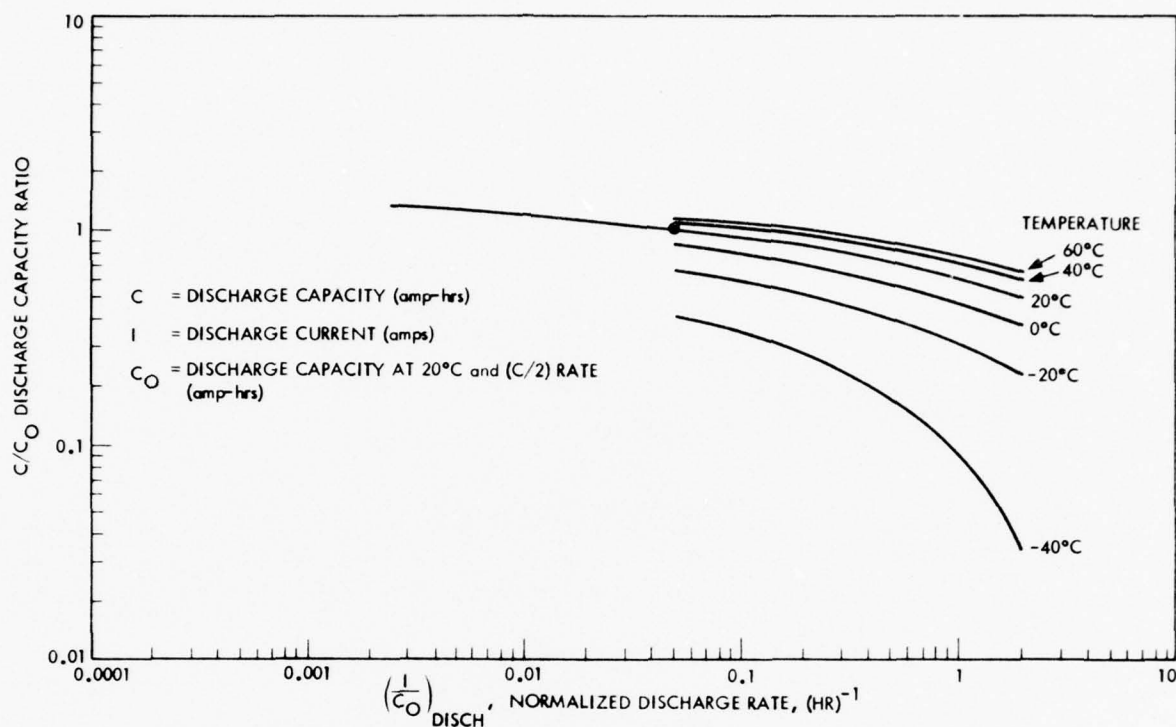
FIGURE 3-10. LEAD - ACID BATTERIES VARIATION IN DISCHARGE
CAPACITY WITH TEMPERATURE AND DISCHARGE RATE

Since the normalized discharge rate for operation on a buoy is as low as
0.0005 hr^{-1}, the data in Figure 3-10 indicate that battery discharge
capacities as high as 50 percent greater than the capacity under standard
discharge rates may be utilized for these Coast Guard applications.

Current-Voltage characteristics of lead-acid batteries at 20°C are shown
in Figure 3-11. (References 9, 10, 13, 14, 15). The voltages in Fig-
ure 3-11 may be adjusted for other temperature by use of the following
(Reference 9):

$$\left(\frac{V_c - V_{co}}{T_c - T_{co}}\right) = -0.0035 \text{ volts/°F} \tag{3-3}$$

3-9
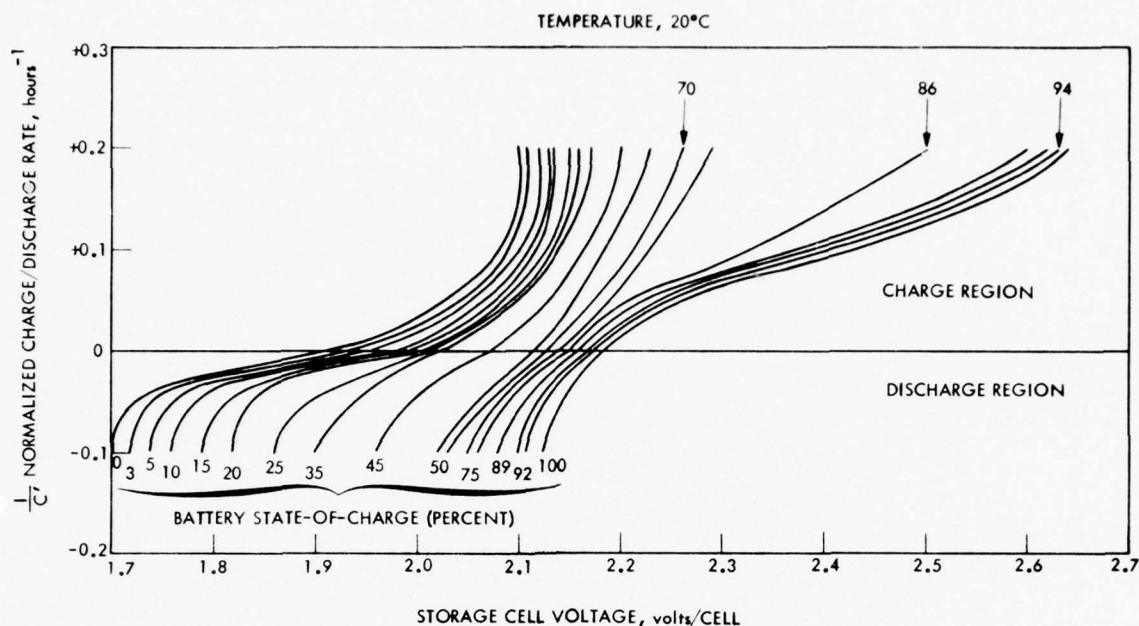
FIGURE 3-11.   LEAD-ACID BATTERY, CURRENT - VOLTAGE CHARACTERISTICS

where

V_c = Storage Cell Voltage at Tc, volts/cell

V_{co} = Storage Cell Voltage at T_{co}, volts/cell

T_c = Storage Cell Temperature, °F

T_{co} = Storage Cell Reference Temperature, °F

The instantaneous charge efficiency of lead-acid batteries is given in Figure 3-12. (References 5, 9, 12). A characteristic of these storage cells is the decrease in charge efficiency with increasing charging currents.

The effect of depth-of-discharge on lead-acid battery cycle life is shown in Figure 3-13. (Reference 11). The data presently used in the DSPA Computer Program is also shown. This data is only an engineering estimate and should be updated as the latest information from the NAD-Crane tests on lead-acid batteries is received.

$\dfrac{1}{C}$ = NORMALIZED CHARGE CURRENT, $\dfrac{\text{ampere}}{\text{ampere-hour}}$
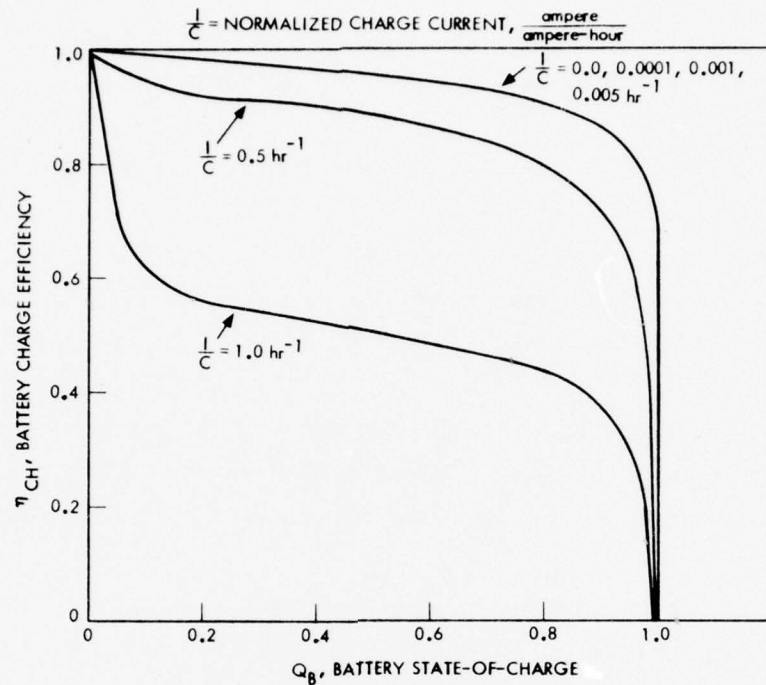
FIGURE 3-12. LEAD – ACID BATTERIES, INSTANTANEOUS CHARGE EFFICIENCY
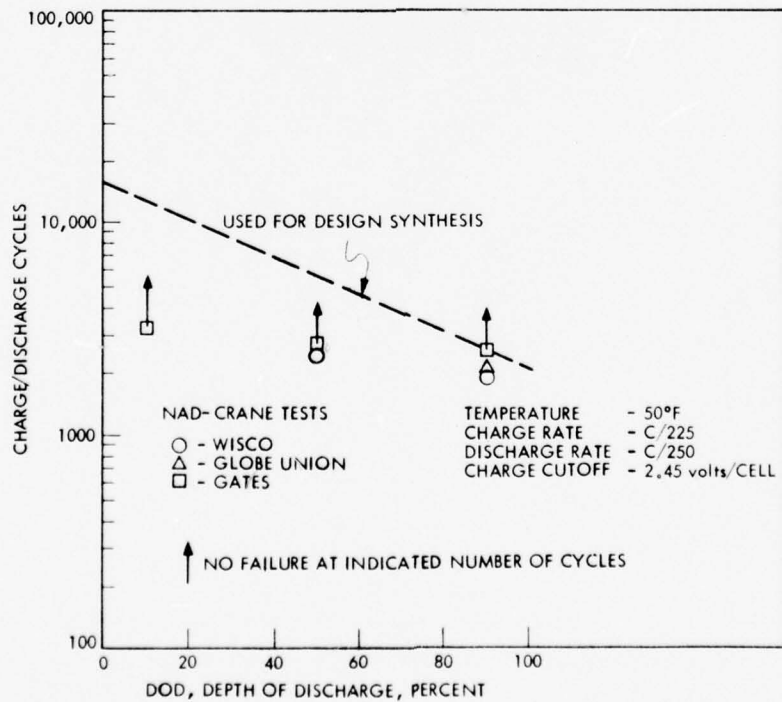
FIGURE 3-13. CHARGE/DISCHARGE CYCLE LIFE OF Pb – ACID BATTERIES

Maximum allowable charging currents for lead-acid Batteries are shown in Figure 3-14 (Reference 15). The allowable current values are used to estimate the current cutoff on a battery charger.

Electrolyte characteristics for lead-acid batteries are illustrated in Figures 3-15 and 3-16 (Reference 15). Both electrolyte specific gravity and freezing point are shown. As the data in Figure 3-10 shows, when the electrolyte temperature approaches the freezing point, battery discharge capacity falls off sharply.

Most of the information on nickel-cadmium (Ni-Cd) batteries, supplied with the DSPA Computer Program, was based on the results of tests on Ni-Cd storage cells used for the Viking Orbiter spacecraft (Reference 3).

Typical information used in determining appropriate Ni-Cd battery performance is shown in Figures 3-17 and 3-18 (Reference 16). Current-voltage
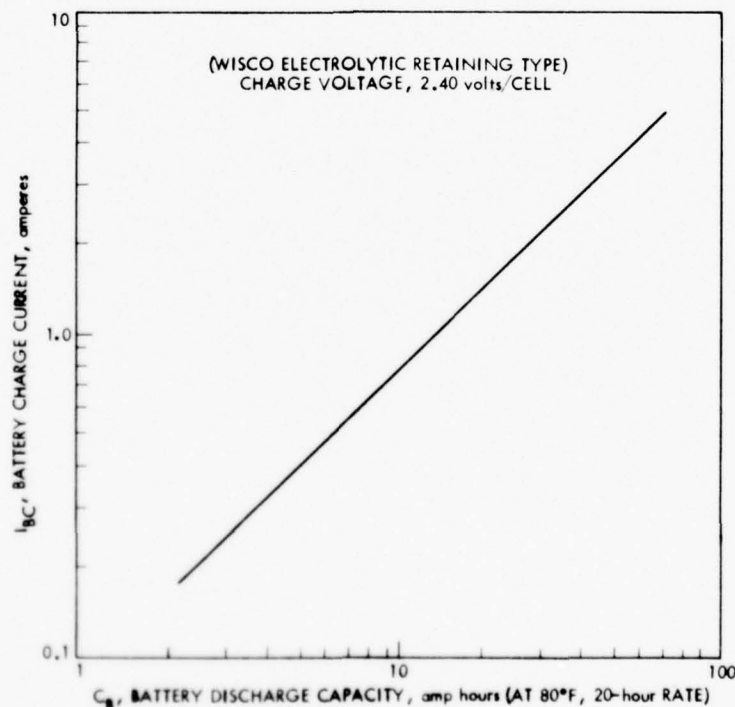
FIGURE 3-14. MAXIMUM BATTERY CHARGE CURRENT, LEAD - ACID BATTERIES

(1) For "DD" TYPES
(2) For "DA" "DH" and "DHB" TYPES

ELECTROLYTE
SPECIFIC GRAVITY (80°F)
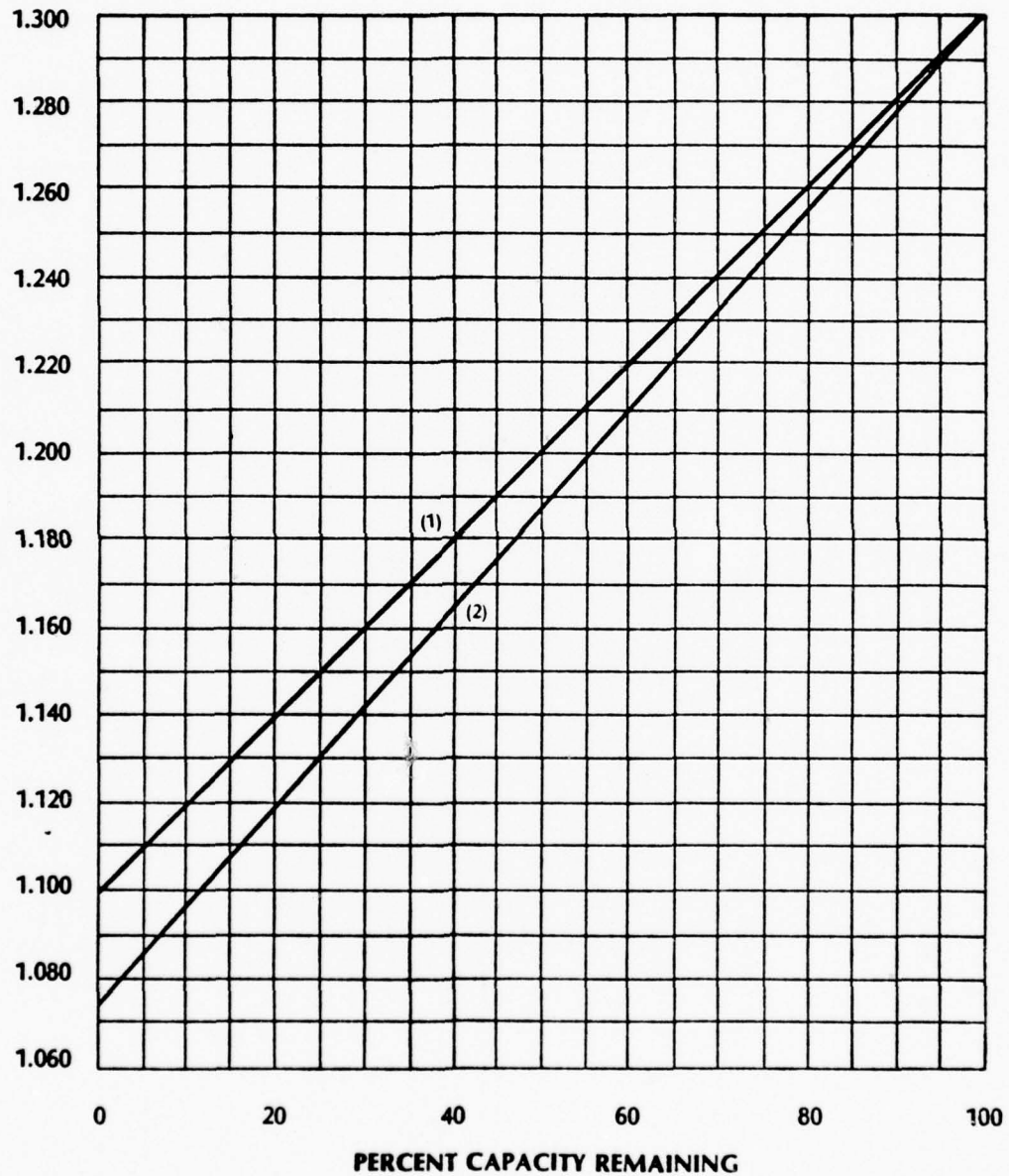
FIGURE 3-15.   ELECTROLYTE SPECIFIC GRAVITY, WISCO LEAD - ACID BATTERIES
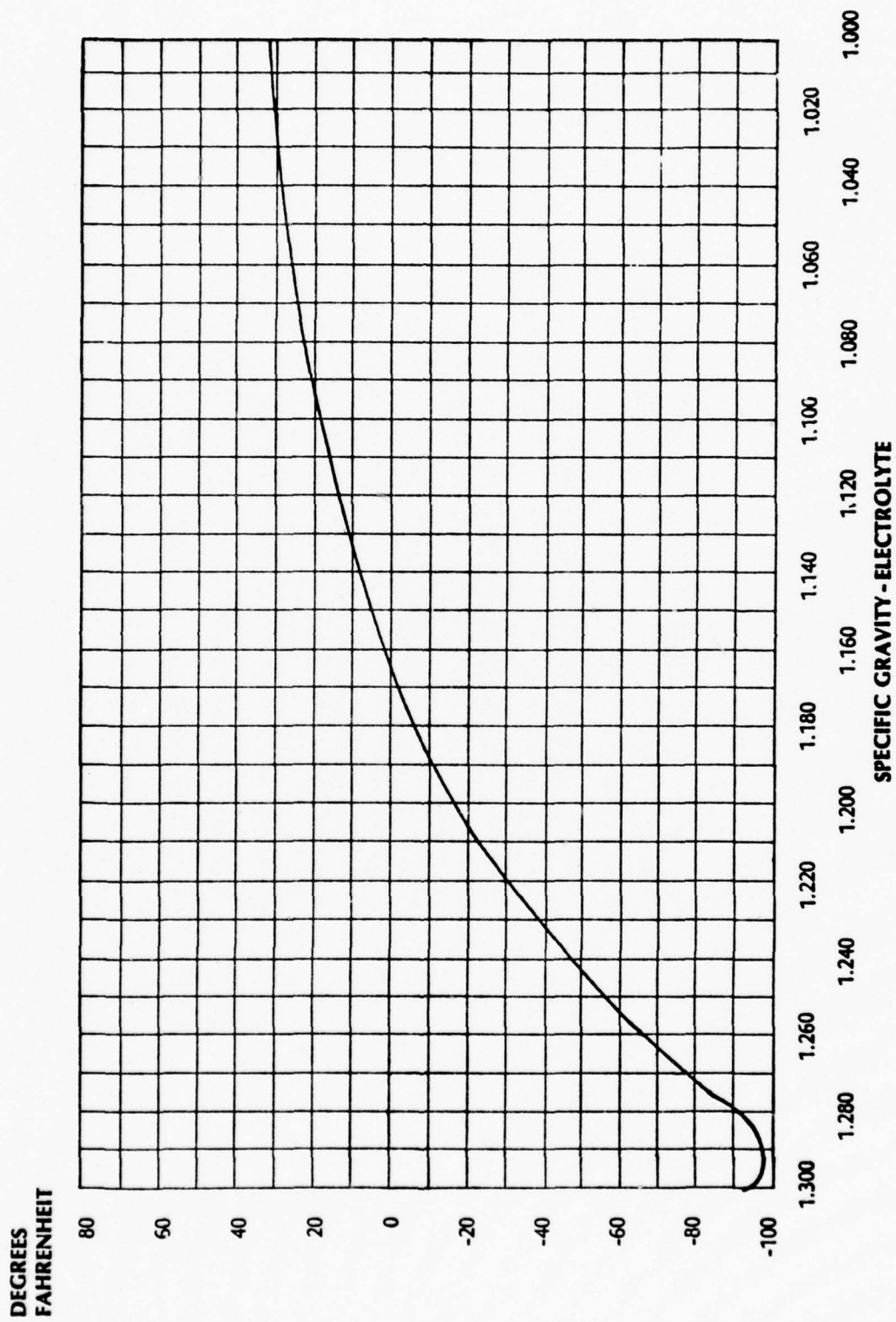
FIGURE 3-16. ELECTROLYTE FREEZING POINT, WISCO LEAD – ACID BATTERIES
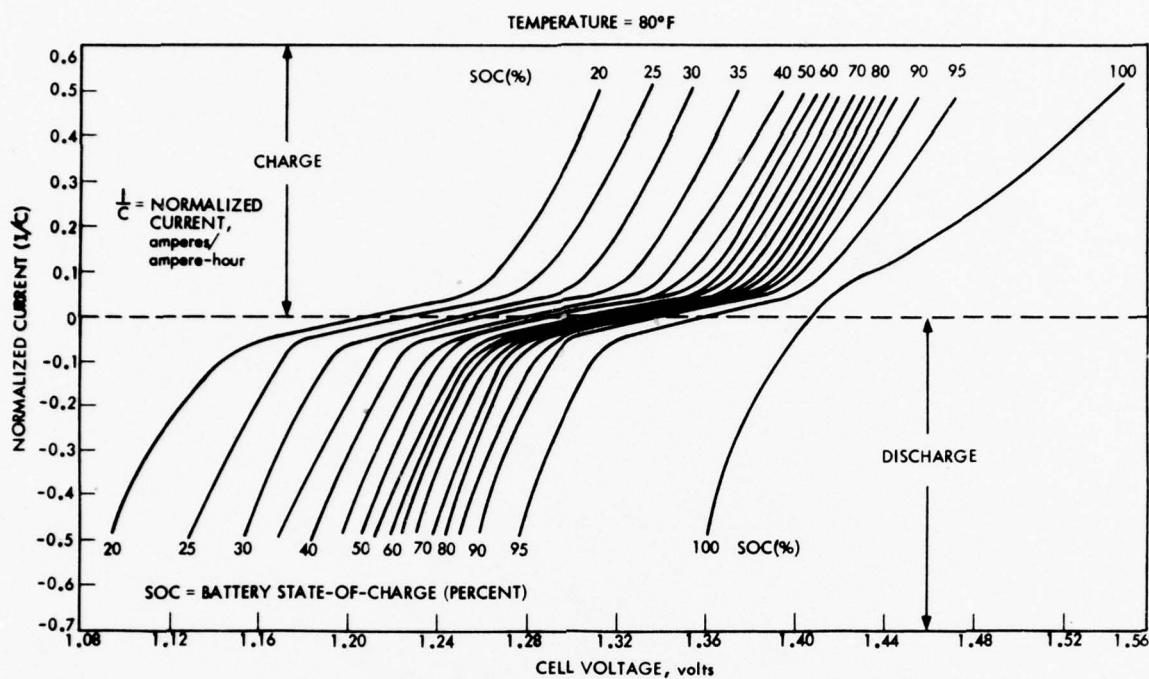
FIGURE 3-17. NICKEL – CADMIUM BATTERIES, CURRENT – VOLTAGE CHARACTERISTICS
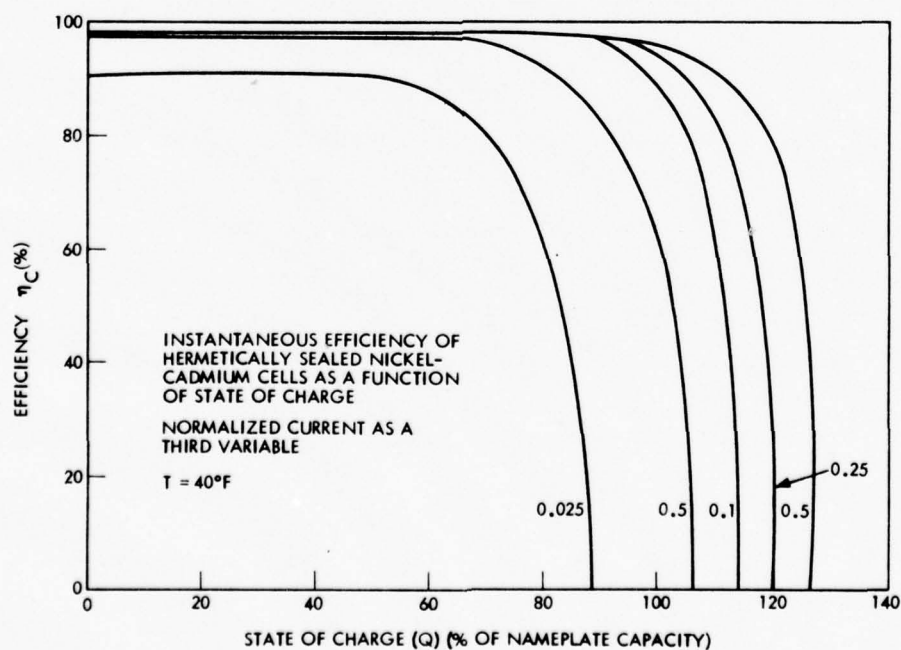
FIGURE 3-18. NICKEL – CADMIUM BATTERIES, CHARGE EFFICIENCY

characteristics of Ni-Cd storage cells are shown in Figure 3-17. Instantaneous charge efficiencies of these cells are illustrated in Figure 3-18. The data in Figure 3-18 show that the charge efficiency of Ni-Cd batteries increases as charge rate increases (the opposite of lead-acid batteries).

Cycle life of Ni-Cd batteries for use in design synthesis is given in Figure 3-19 (Reference 17).

The characteristics of a series regulator used as a battery charger by the Coast Guard is shown in Figure 3-20 (Reference 5). This regulator has no current limit to prevent excessive charging currents.

3.3 Power Conditioning and Distribution Group

The load requirements on the power system are based on various lamp/flasher combinations. Two types of lamps are under consideration: tungsten filament lamps which are currently in use and xenon flash lamps (over a current range which yields illumination levels equal to the tungsten lamps).
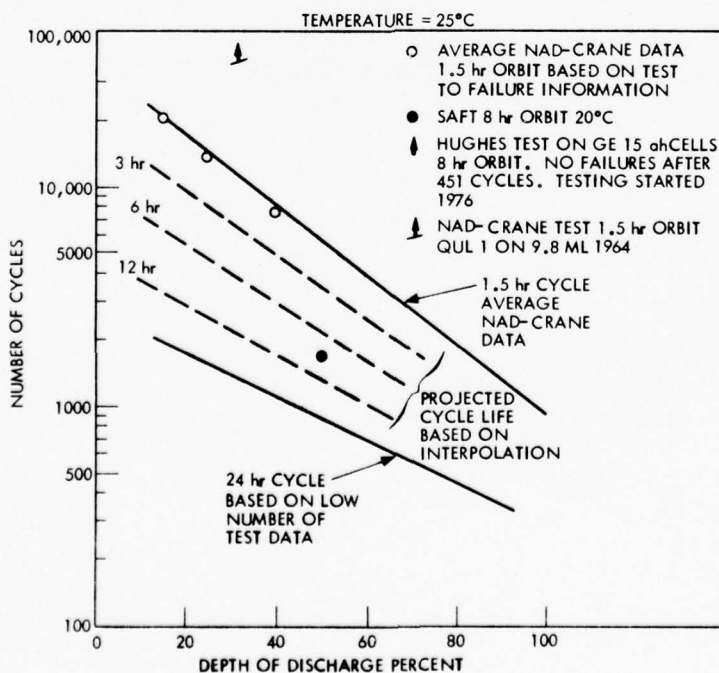
FIGURE 3-19.   CHARGE/DISCHARGE CYCLE LIFE OF NICKEL - CADMIUM BATTERIES
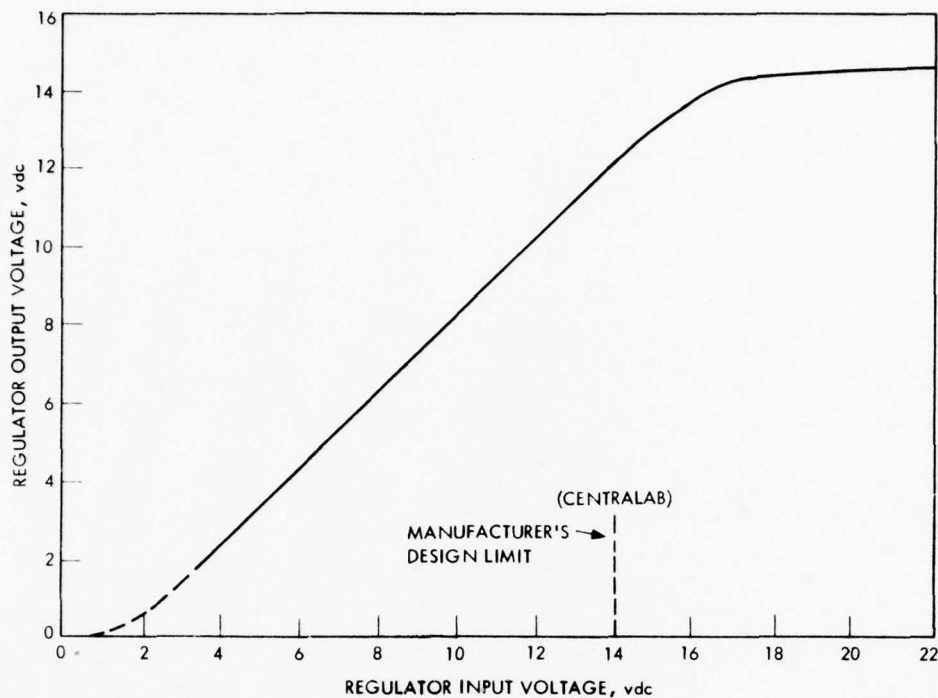
FIGURE 3-20. BATTERY CHARGER (REGULATOR) CHARACTERISTICS

(The figure shows a plot of REGULATOR OUTPUT VOLTAGE, vdc (y-axis, 0 to 16) versus REGULATOR INPUT VOLTAGE, vdc (x-axis, 0 to 22), with markings for MANUFACTURER'S DESIGN LIMIT and (CENTRALAB).)

Flasher types are those presently under development or operational with the Coast Guard (Reference 18), i.e.:

- Type I   – Simple Flashing.

- Type II   – Group Flashing.

- Type III   – Complex Flashing.

- Type IV   – Fixed.

These flashers have the characteristics indicated below:

<u>Type I</u> – Simple flashing consisting of a flash of F_1 seconds, alternating with an eclipse of E_1 seconds, the total period being $E_1 + F_1$ seconds. The most common Type I characteristics are specified in Table 3-1.

<u>Type II</u> – Group flashing consisting of a group of N flashes all of the same duration F_1, with the inter-flash eclipse of duration E_1, the intergroup eclipse of duration E_2, and the overall period of $NF_1 + (N - 1) E_1 + E_2$. Common Type II characteristics are in Table 3-2.

TABLE 3-1.-TYPE I FLASHER CHARACTERISTICS

F_1	E_1	Characteristic Mrkg.	Duty Cycle
0.3 seconds	0.7 seconds	QK FL (0.5)	0.300
0.5	2.0	FL 2.5 (0.5)	0.200
0.4	3.6	FL 4 (0.4)	0.100
1.0	5.0	FL 6 (1.0)	0.167
3.0	3.0	E INT 6 (3.0)	0.500
3.0	1.0	OCC 4 (3.0)	0.750

TABLE 3-2.-TYPE II FLASHER CHARACTERISTICS

N	F_1	E_1	E_2	Characteristic Marking	Duty Cycle
6	0.3 seconds	0.7 seconds	4.7 seconds	I QK FL (6X0.3)	0.180
2	0.4 seconds	0.6 seconds	3.6 seconds	GP FL 5 (2X0.4)	0.160

TYPE III - Complex flashing consisting of any other combination of short and long flashes (F_1, F_2, etc.) and short and long eclipses (E_1, E_2, etc.). The only common characteristic of this type is the Morse Code "A," indicated in Table 3-3.

TABLE 3-3.-TYPE III FLASHER CHARACTERISTICS
(MORSE CODE "A")

F_1	E_1	F_2	E_2	Characteristic Marking	Duty Cycle
0.4 seconds	0.6 seconds	2.0 seconds	5.0 seconds	MO(A)(0.4,2,0)	0.300

Type IV - A flasher with a fixed characteristic will provide all the operational features of the other types but will allow the lamp to burn steadily with no time-coding imposed on the voltage. The characteristic marking is "FIX" and the "duty cycle" marking is "1.000."

The data shown above have been incorporated in the DSPA Computer Program. The program user may then simply select a desired flasher by using the code number indicated in Table 3-4.

Nominal currents (for Tungsten Lamps) are in the range 0.25 amperes - 3.05 amperes (Reference 18). The nominal current must be adjusted for cold filament surge at lamp turn-on. Values of the cold filament surge coefficient are shown in Figure 3-21 (Reference 19).

Voltage regulation characteristics of the flasher regulator are shown in Figure 3-22 (Reference 18). This regulator is only under load when the lamp is turned on.

TABLE 3-4.-FLASHER CODE NUMBERS

IFTYPE (CODE NUMBER)	CHARACTERISTIC MARKING
1	QKFL (0.3)
2	FL 2.5 (0.5)
3	FL 4 (0.4)
4	FL 6 (1.0)
5	EINT 6 (3.0)
6	OCC 4 (3.0)
7	IQKFL (6 x 0.3)
8	GPFLS (2 x 0.4)
9	MO(A) (0.4,2.0)
10	FIX
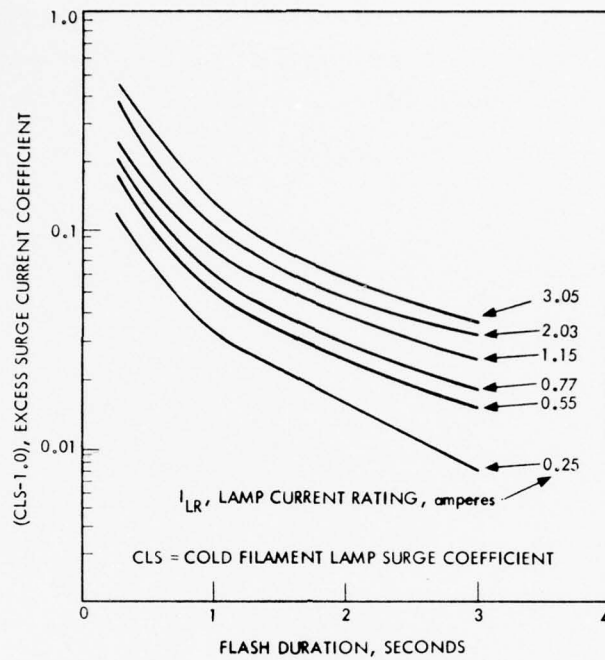
FIGURE 3-21.   COLD FILAMENT LAMP SURGE COEFFICIENTS
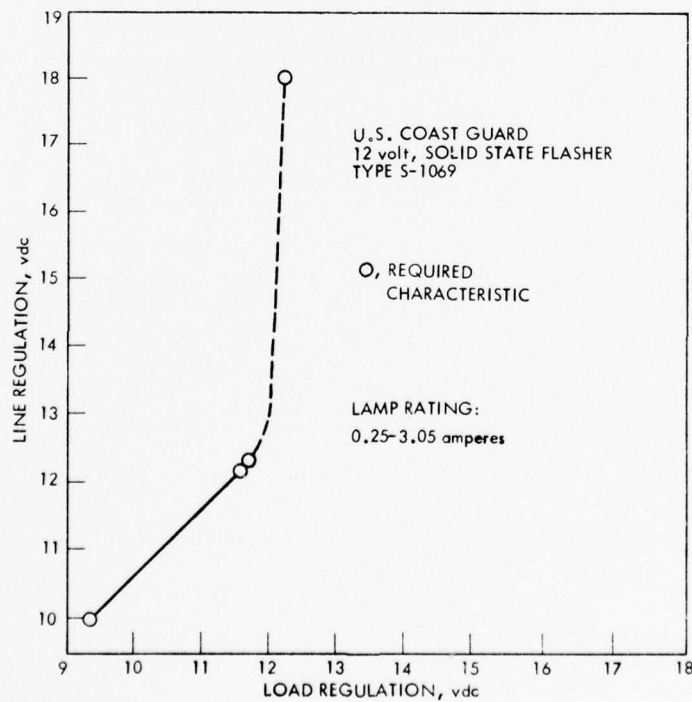
FIGURE 3-22.   LAMP FLASHER SERIES REGULATOR SPECIFICATIONS

Characteristics of the "housekeeping" load regulator are shown in Figure 3-23 (Reference 5). These "housekeeping" loads are always effective and represent a permanent load on the power system.
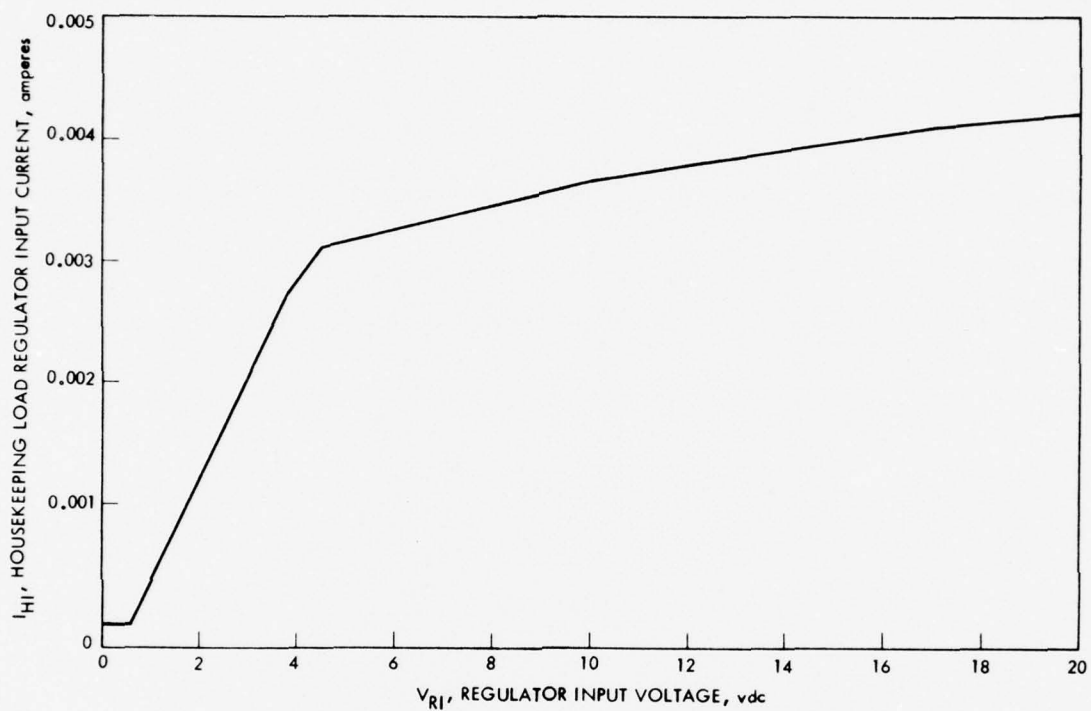
FIGURE 3-23. HOUSEKEEPING LOADS - AIDS TO NAVIGATION

4. PROGRAM VERIFICATION

The final phase in the development of the DSPA Computer Program was program verification. For this phase, the Coast Guard supplied JPL with performance data on five actual solar array/battery power system designs.

The purpose of program verification was to provide a check on the validity of the performance analysis segment of the program by comparison of the predicted operational characteristics of a known power system with the actual operational characteristics of that same power system. The power systems against which the comparisons were made were selected from those presently undergoing instrumented tests at the Coast Guard R&D Center. Recorded values of all critical parameters, from these tests, were made available to JPL by the U.S. Coast Guard (References 5, 12).

Major characteristics of the five power systems used in this comparison are shown in Table 4-1; while, the general arrangement of the power system equipment is shown in Figure 4-1. The information in Table 4-1 indicates that, to all intents and purposes, Systems No. 26 and 29 are identical.

Another key performance parameter measured by the Coast Guard was solar array current degradation — shown in Figures 4-2 to 4-6. Relatively erratic performance was demonstrated by the solar arrays on Systems 2 and 9. The System 47 solar array also experienced erratic performance due to corrosion effects early in the test. In fact, the only two arrays declared successful by the Coast Guard for purposes of verification were those used for Systems 26 and 29.

The major parameter used to determine successful prediction of power system operation was battery state-of-charge. The reason for using this parameter was that if battery charge drops to zero at any time during a mission the power system is considered to have failed.

TABLE 4-1.—NAVAID POWER SYSTEM CHARACTERISTICS

System Number	Solar Array	Array Isolation Diode	Shunt Limiter	Battery	Lamp (amp)
2	Heliotek HGL-V-3785-03 1cm x 2cm P on N cells* 40 cells-in-series 15 cells-in-parallel	1N1341A	Heliotek	Globe; 12 volts 20 amp-hours/ battery 3 batteries- in-parallel	0.55
9	Heliotek HGL-V-3785-03* Same as system No. 2	1N1341A	Heliotek	Gates; 2.1 volts/cell 6 cells-in- series 5 amp-hours/ battery 12 batteries- in-parallel	0.55
26	Heliotek HW-3785-04 1cm x 2cm P on N cells* 33 cells-in-series 15 cells-in-parallel	1N1341A		WISCO; 12 volts (2 batteries- in-series) 100 amp-hours/ battery	0.77
29	Heliotek HW-3785-02* Same as system No. 26	1N1341A		Same as system No. 26	0.77

*See Figure 3-2.

TABLE 4-1.-NAVAID POWER SYSTEM CHARACTERISTICS (contd)

System Number	Solar Array	Array Isolation Diode	Shunt Limiter	Battery	Lamp (amp)
47	Centralab No. 17 2cm x 2cm P on N cells** 48 cells-in-series 6 cells-in-parallel	1N2992		Globe; 12 volts 20 amp-hours/ battery 2 batteries- in-parallel	0.55
*See Figure 3-3					
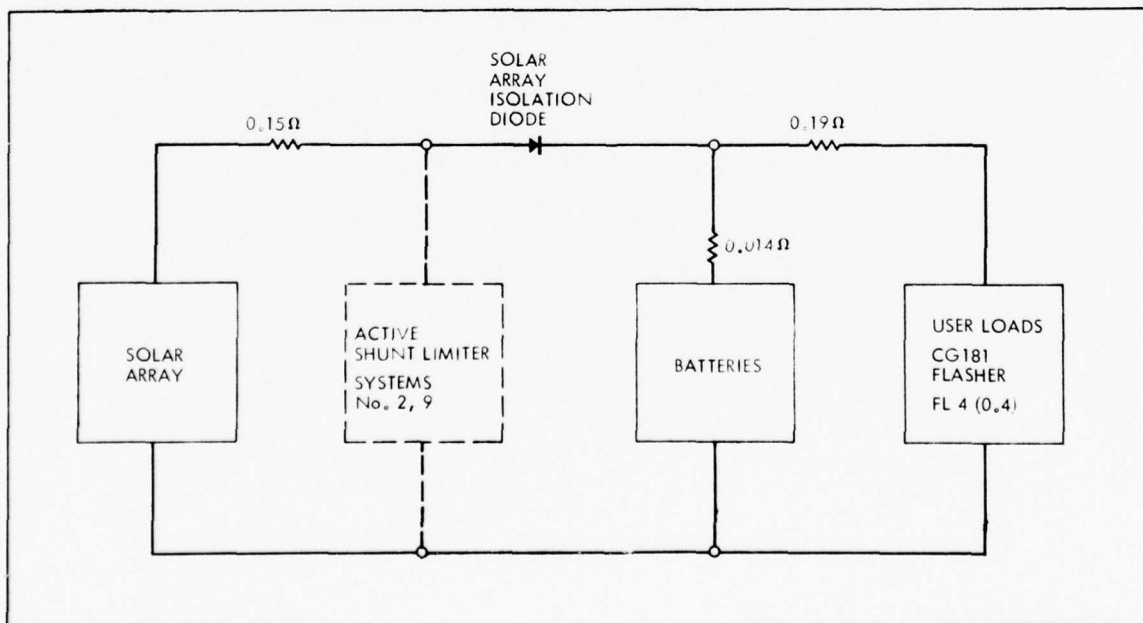
FIGURE 4-1. POWER SYSTEMS TESTED BY U.S. COAST GUARD
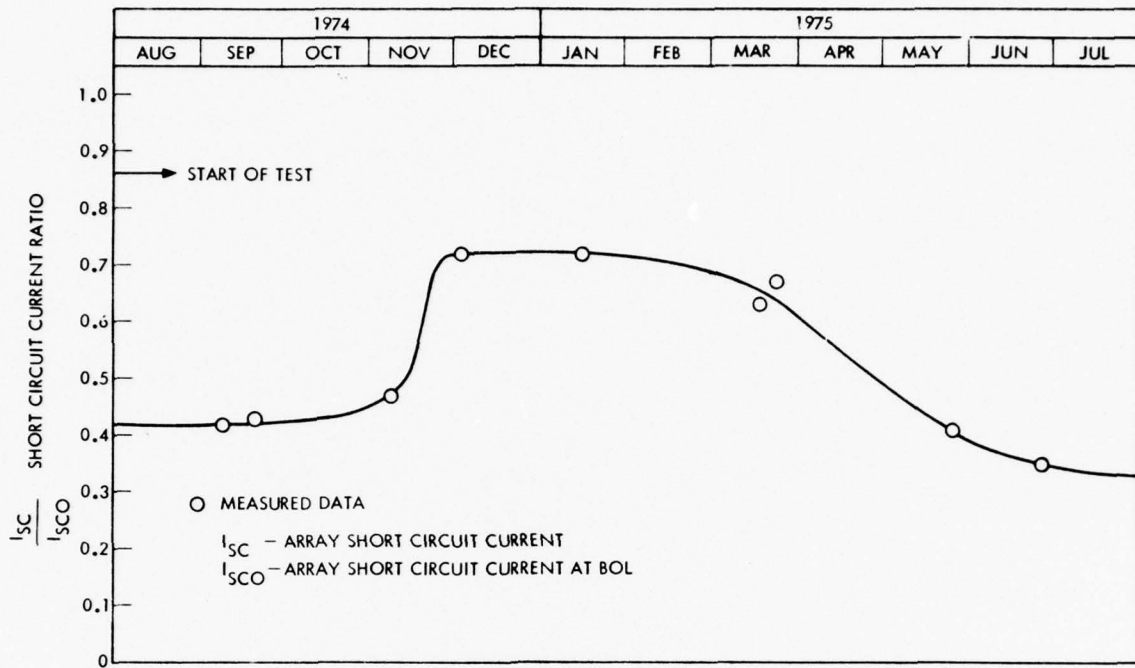
FIGURE 4-2.   SOLAR ARRAY CURRENT DEGRADATION SYSTEM NO. 2
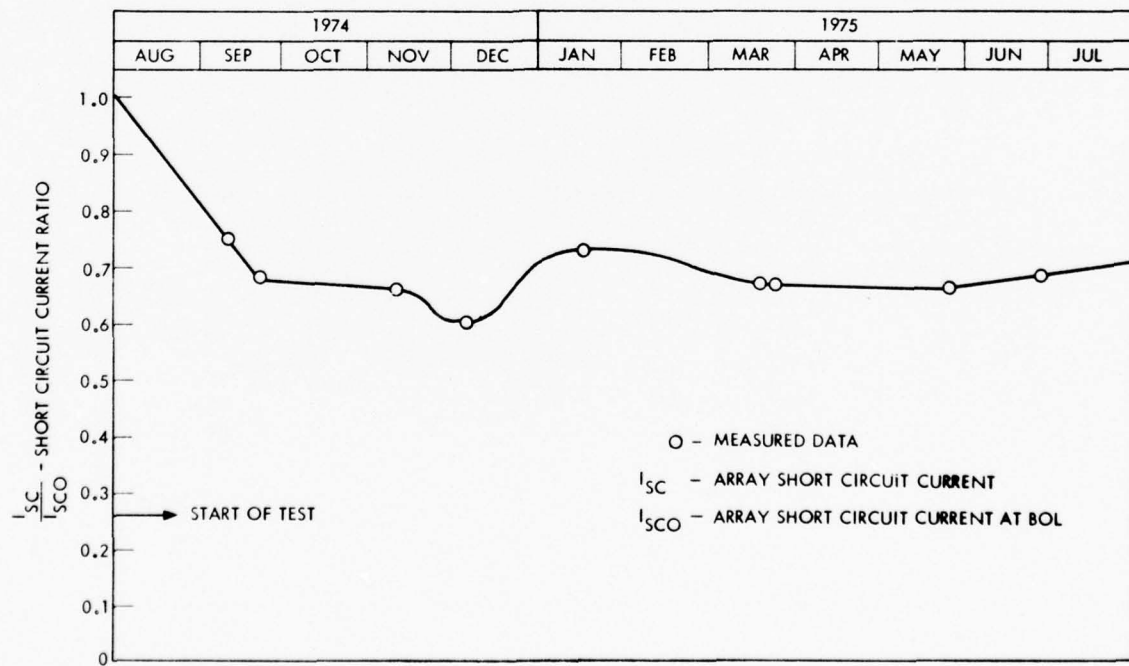
FIGURE 4-3.   SOLAR ARRAY CURRENT DEGRADATION NO. 9
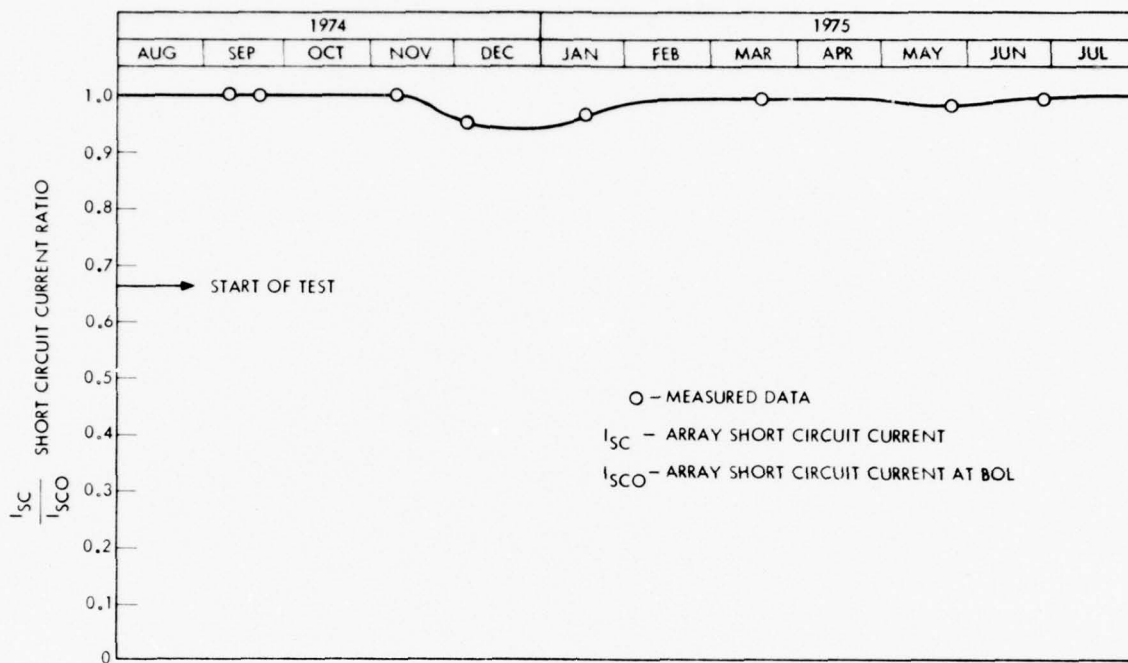
FIGURE 4-4.   SOLAR ARRAY CURRENT DEGRADATION SYSTEM NO. 26
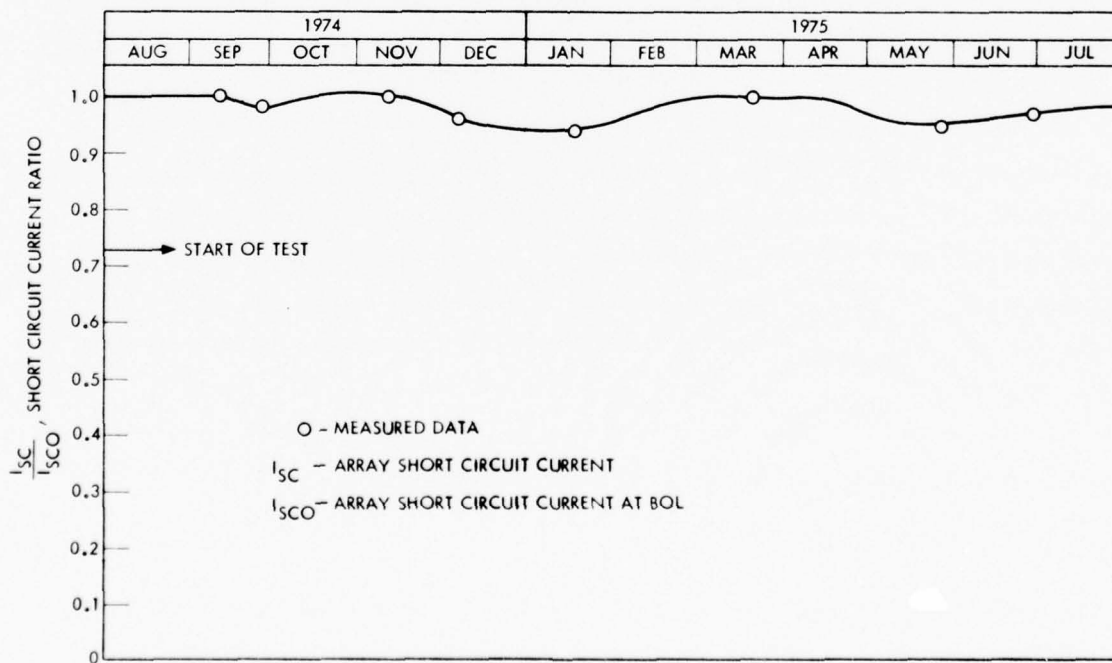
FIGURE 4-5.   SOLAR ARRAY CURRENT DEGRADATION SYSTEM NO. 29
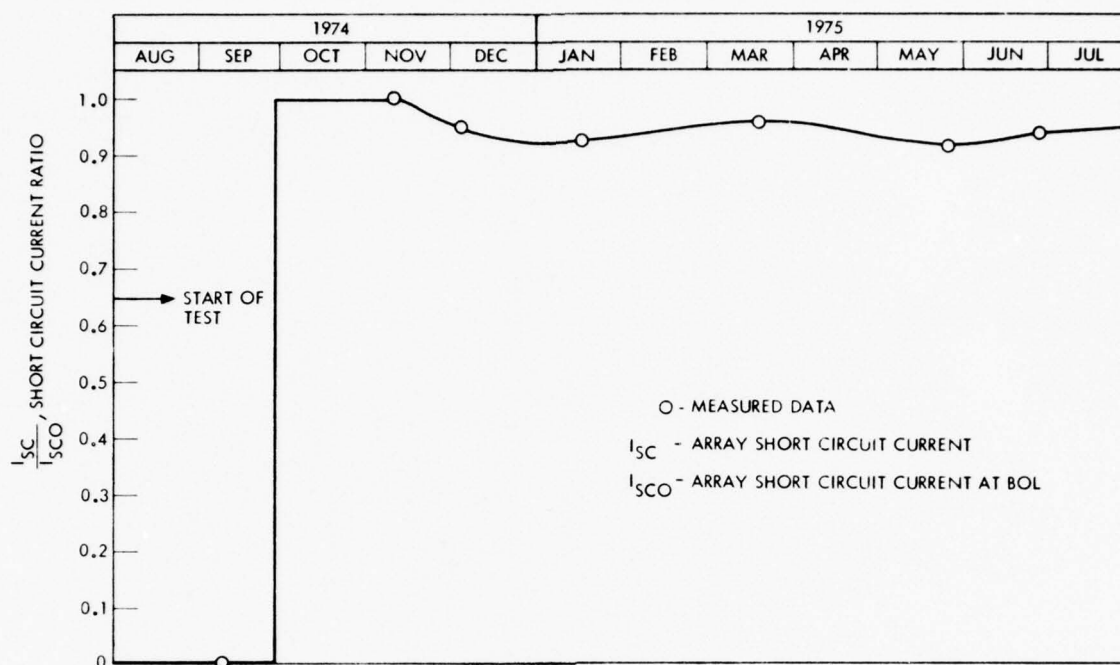
FIGURE 4-6. SOLAR ARRAY CURRENT DEGRADATION SYSTEM NO. 47

The results of the verification tests of the DSPA Computer Program are shown in Figures 4-7 to 4-11. Each of these figures shows two values for the battery storage capacity. The standard capacity (CBSTD) was taken from Table 4-1 (except in the case of System 9 where, for convenience, the battery capacities were doubled, and the batteries-in-parallel were halved). These values represent battery capacity at the standard discharge rate of 0.05 ampere/ampere-hour (see Figure 3-10). However, as the battery discharge rate decreases, the storage capacity of the battery increases. Hence, the "actual" battery capacities (CB) are also shown in Figures 4-7 to 4-11. These values of CB represent the battery capacities used as input to the DSPA computer program which enabled the program to predict the battery state-of-charge (as a function of time) shown in Figures 4-7 to 4-11.

The predicted battery states-of-charge for Systems 2 and 9 were still a fair approximation of the measured state-of-charge in spite of the erratic performance of the solar arrays for these systems.
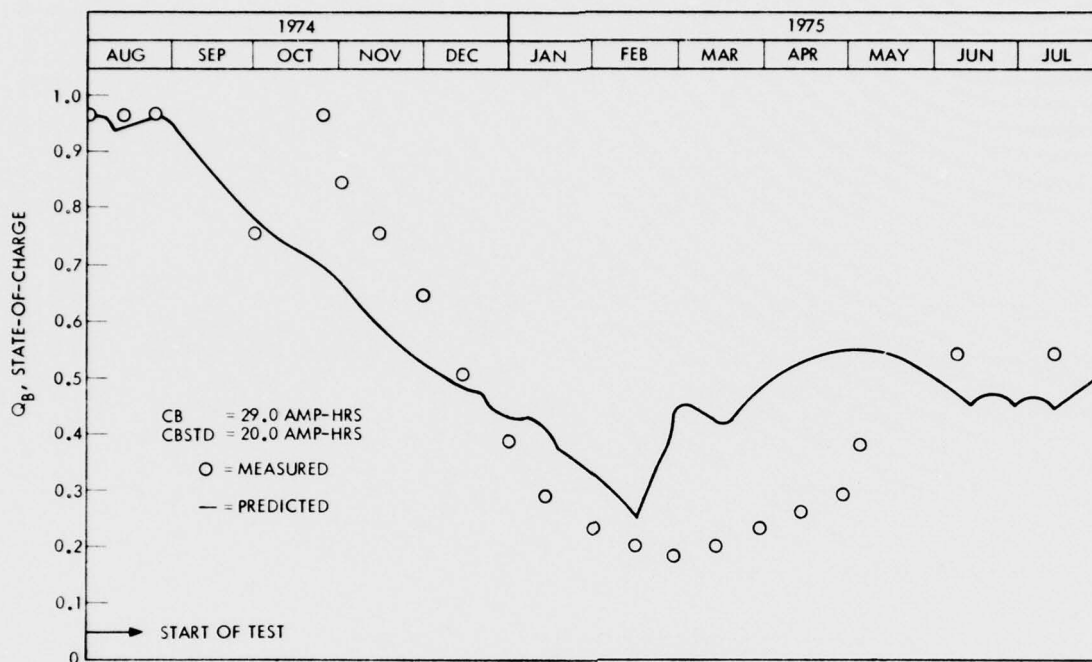
FIGURE 4-7. COMPUTER PROGRAM VERIFICATION TEST SYSTEM NO. 2
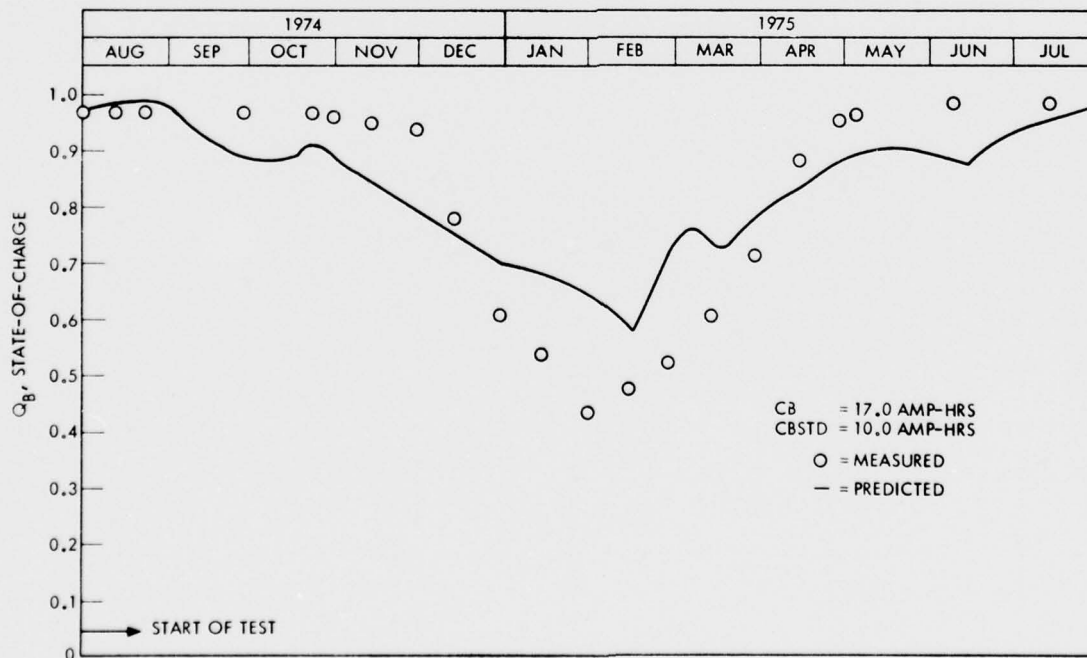
FIGURE 4-8. COMPUTER PROGRAM VERIFICATION TEST SYSTEM NO. 9
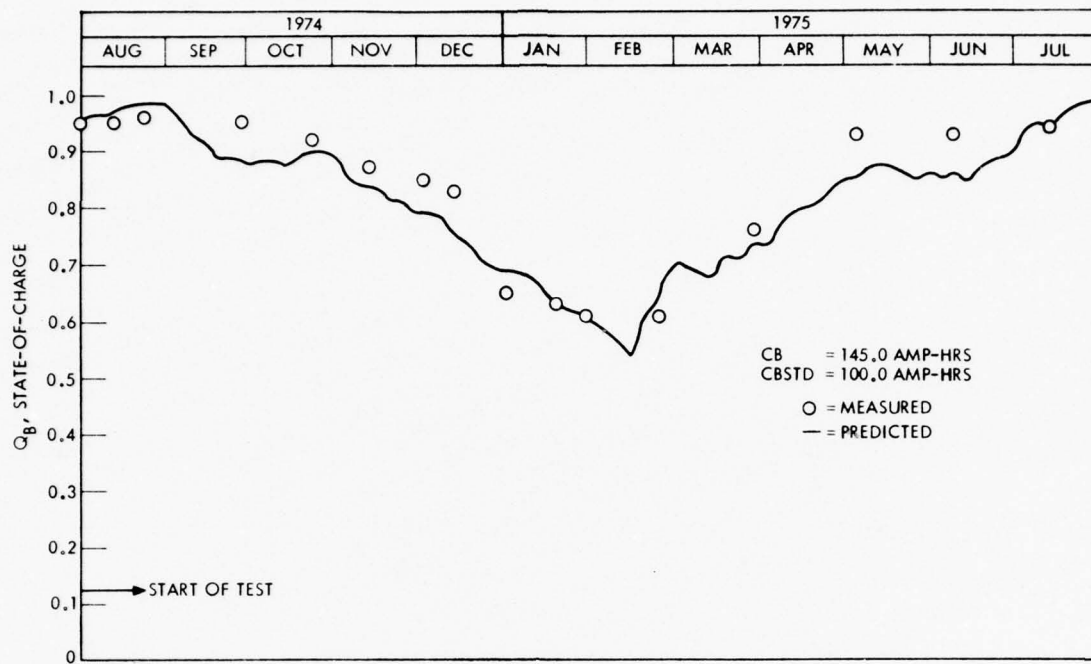
FIGURE 4-9.   COMPUTER PROGRAM VERIFICATION TEST SYSTEM NO. 26
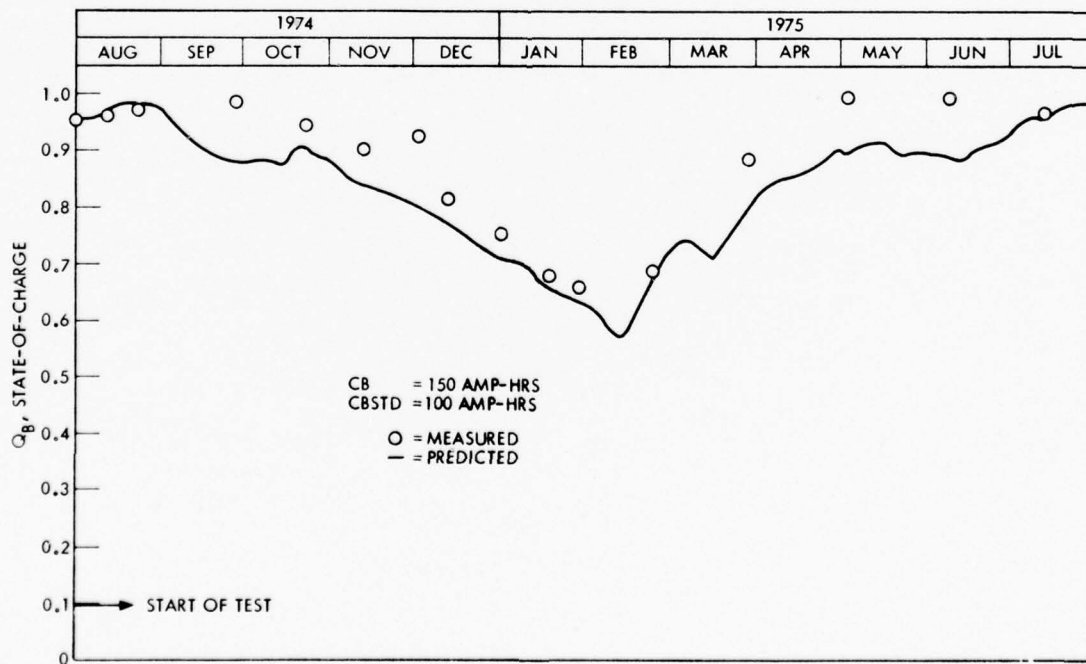
FIGURE 4-10.   COMPUTER PROGRAM VERIFICATION TEST SYSTEM NO. 29
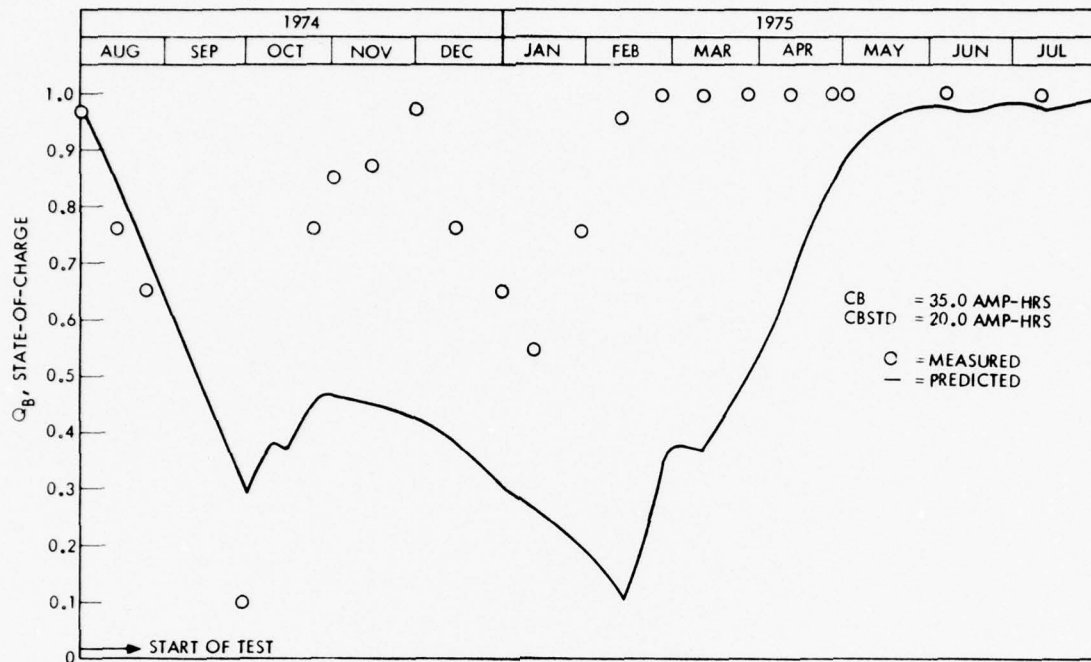
FIGURE 4-11. COMPUTER PROGRAM VERIFICATION TEST SYSTEM NO. 47

Predicted battery states-of-charge for Systems 26 and 29 were very close to the measured states-of-charge. These predictions made with success-ful power systems are a true measure of the capability of the DSPA com-puter program to simulate power system operation over a one year period.

The final verification test performed with System 47 data only shows a general trend agreement between measured and predicted battery state-of-charge. This is due to the initial corrosion failure of the solar array with the attendant erratic operation. This comparison is not consid-ered a true test of the DSPA Computer Program capabilities.

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18. "Purchase Description for 12-Volt, Solid-State Flasher for Maritime Aids to Navigation," Purchase Description No. 181B, U.S. Coast Guard, Washington D.C., May 13, 1968.

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APPENDIX A
BALANCED POWER SYSTEMS

LIST OF FIGURES

A schematic of the Navigation Aid Power system is shown in Figure A-1.

There are three operational modes for this power system, i.e.:

- Power Source Group Only.

- Battery Only.

- Share-Mode.

When there is no power available from the Power Source Group (PSG), then the loads are supplied only by the battery. Hence, the energy balance is:

$$(P_{PCD})_J \, (\Delta t)_J = \eta_D \, (P_{BD})_J \, (\Delta t)_J \tag{A-1}$$

where:

$(\Delta t)_J$ = Incremental load periods during Power Source Group shutdown, hours

$(P_{PCD})_J$ = Power Conditioning and Distribution Group (PCDG) loads during PSG shutdown, watts

$(P_{BD})_J$ = Battery Discharge Power during PSG shutdown, watts

η_D = Efficiency of battery discharge device
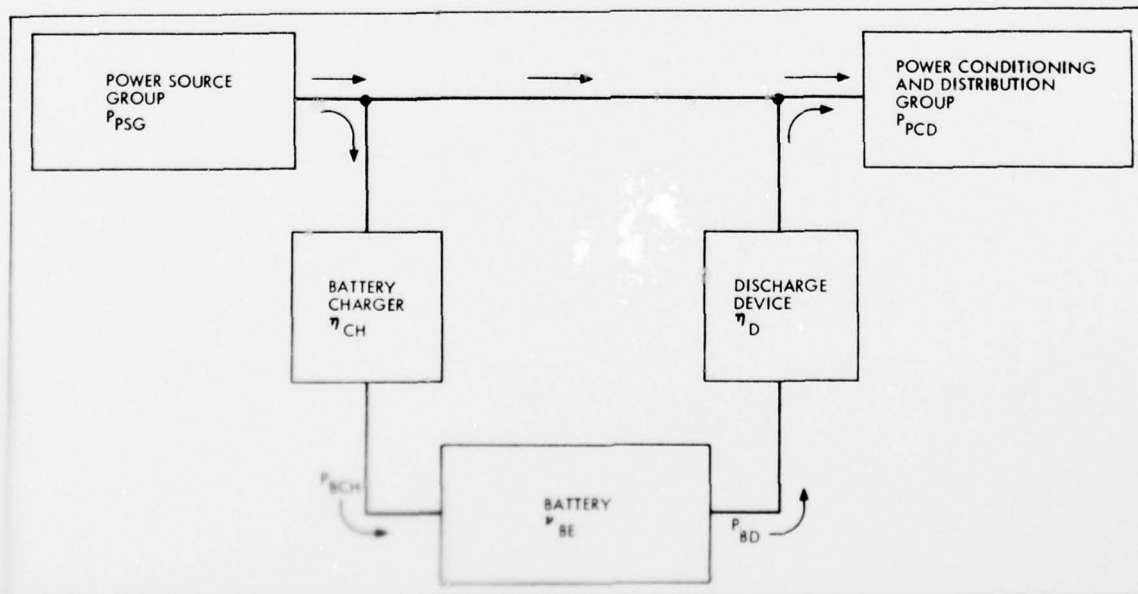
FIGURE A-1. NAVIGATION AID POWER SYSTEM

During Share-Mode operation when the loads are supplied by both the Power Source Group and the battery, the energy balance is:

$$(P_{PCD})_K \, (\Delta t)_K = \overline{P_{PSG}} \, (\Delta t)_K + \eta_D \, (P_{BD})_K \, (\Delta t)_K \qquad \text{(A-2)}$$

where:

$(\Delta t)_K$ = Incremental load periods during share-mode operation power, hours

$\overline{P_{PSG}}$ = Average Power Source Group power output, watts

$(P_{BD})_K$ = Battery Discharge Power during Share-Mode operation, watts

$(P_{PCD})_K$ = PCDG loads during Share-Mode operation, watts

When the Power Source Group alone supplies energy for charging the battery and for powering the loads, the energy balance is:

$$\overline{P_{PSG}} \, (\Delta t)_L = (P_{PCD})_L \, (\Delta t)_L + \frac{(P_{BCH})_L \, (\Delta t)_L}{\eta_{CH}} \qquad \text{(A-3)}$$

where:

$(\Delta t)_L$ = Incremental load periods when PSG is charging the battery and powering the loads, hours

η_{CH} = Battery charger efficiency

$(P_{BCH})_L$ = Battery Charge Power during charging periods, watts

$(P_{PCD})_L$ = PCDG loads during battery charge periods, watts

During the PSG shutdown periods:

$$(E_{BD})_J = (P_{BD})_J \, (\Delta t)_J \qquad \text{(A-4)}$$

where: $(E_{BD})_J$ = Battery energy discharged during PSG shutdown periods, watts-hours

During PSG and Battery Share-Mode periods:

$$(E_{BD})_K = (P_{BD})_K \, (\Delta t)_K \qquad\qquad (A-5)$$

where: $(E_{BD})_K$ = Battery energy discharged during Share-Mode periods, watt-hours

Combining Eqs. (A-1) and (A-4):

$$(E_{BD})_J = \frac{(P_{PCD})_J \, (\Delta t)_J}{\eta_D} \qquad\qquad (A-6)$$

Combining Eqs. (A-2) and (A-5):

$$(E_{BD})_K = \frac{(P_{PCD})_K \, (\Delta t)_K}{\eta_D} - \frac{\overline{P_{PSG}} \, (\Delta t)_K}{\eta_D} \qquad\qquad (A-7)$$

The total battery discharge energy is:

$$E_{BDT} = (E_{BD})_J + (E_{BD})_K \qquad\qquad (A-8)$$

where: E_{BDT} = Total battery energy discharged during "mission," watt-hours

Combining Eqs. (A-6), (A-7) and (A-8):

$$E_{BDT} = \frac{(P_{PCD})_J \, (\Delta t)_J}{\eta_D} + \frac{(P_{PCD})_K \, (\Delta t)_K}{\eta_D} - \frac{\overline{P_{PSG}} \, (\Delta t)_K}{\eta_D} \qquad\qquad (A-9)$$

During period of battery charge:

$$E_{BCHT} = (P_{BCH})_L \, (\Delta t)_L \qquad\qquad (A-10)$$

where: E_{BCHT} = Total battery charge energy during "mission," watt-hours

Combining Eqs. (A-3) and (A-10):

$$E_{BCHT} = (\eta_{CH}) \; (\overline{P_{PSG}}) \; (\Delta t)_L - (\eta_{CH}) \; (P_{PCD})_L \; (\Delta t)_L \qquad (A\text{-}11)$$

A balanced power system is defined as one wherein the PSG supplies just enough energy to the Energy Storage Group (ESG) to replace that energy discharged by the ESG. Thus:

$$E_{BCHT} = \nu_{BE} \; E_{BDT} \qquad (A\text{-}12)$$

where: ν_{BE} = Battery energy charge/discharge ratio (inverse of battery energy charge efficiency)

Combining Eqs. (A-9), (A-11) and (A-12) and rearranging, the average PSG power level requirement is then:

$$\overline{P_{PSG}} = \frac{(\nu_{BE}) \left[(P_{PCD})_J \; (\Delta t)_J + (P_{PCD})_K \; (\Delta t)_K \right] + (\eta_D \eta_{CH}) \; (P_{PCD})_L \; (\Delta t)_L}{(\eta_D \eta_{CH}) \; (\Delta t)_L + (\eta_{BE}) \; (\Delta t)_K} \qquad (A\text{-}13)$$

Defining:

$$(E_{PCD})_J = (P_{PCD})_J \; (\Delta t)_J \qquad\qquad (A\text{-}14)$$

$$(E_{PCD})_K = (P_{PCD})_K \; (\Delta t)_K \qquad\qquad (A\text{-}15)$$

$$(E_{PCD})_L = (P_{PCD})_K \; (\Delta t)_L \qquad\qquad (A\text{-}16)$$

Load energy (from PCD group) during each of the applicable power system operational modes, watt-hours

Combining Eqs. (A-13), (A-14), (A-15) and (A-16):

$$\overline{P_{PSG}} = \frac{(\nu_{BE}) \left[(E_{PCD})_J + (E_{PCD})_K \right] + (\eta_D \eta_{CH}) \; (E_{PCD})_L}{(\eta_D \eta_{CH}) \; (\Delta t)_L + (\nu_{BE}) \; (\Delta t)_K} \qquad (A\text{-}17)$$

The total energy required of the PSG is thus:

$$E_{PSG} = (\overline{P_{PSG}}) \left[(\Delta t)_K + (\Delta t)_L \right]$$

(A-18)

where: E_{PSG} = Power Source Group Total energy requirement for the "mission," watt-hours

APPENDIX B

ASHRAE ALGORITHMS FOR SOLAR INSOLATION*

LIST OF FIGURES

LIST OF TABLES

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*"Procedure for Determining Heating and Cooling Loads for Computerized Energy Calculations" — American Society of Heating, Refrigerating and Air Conditioning Engineers; 1971.
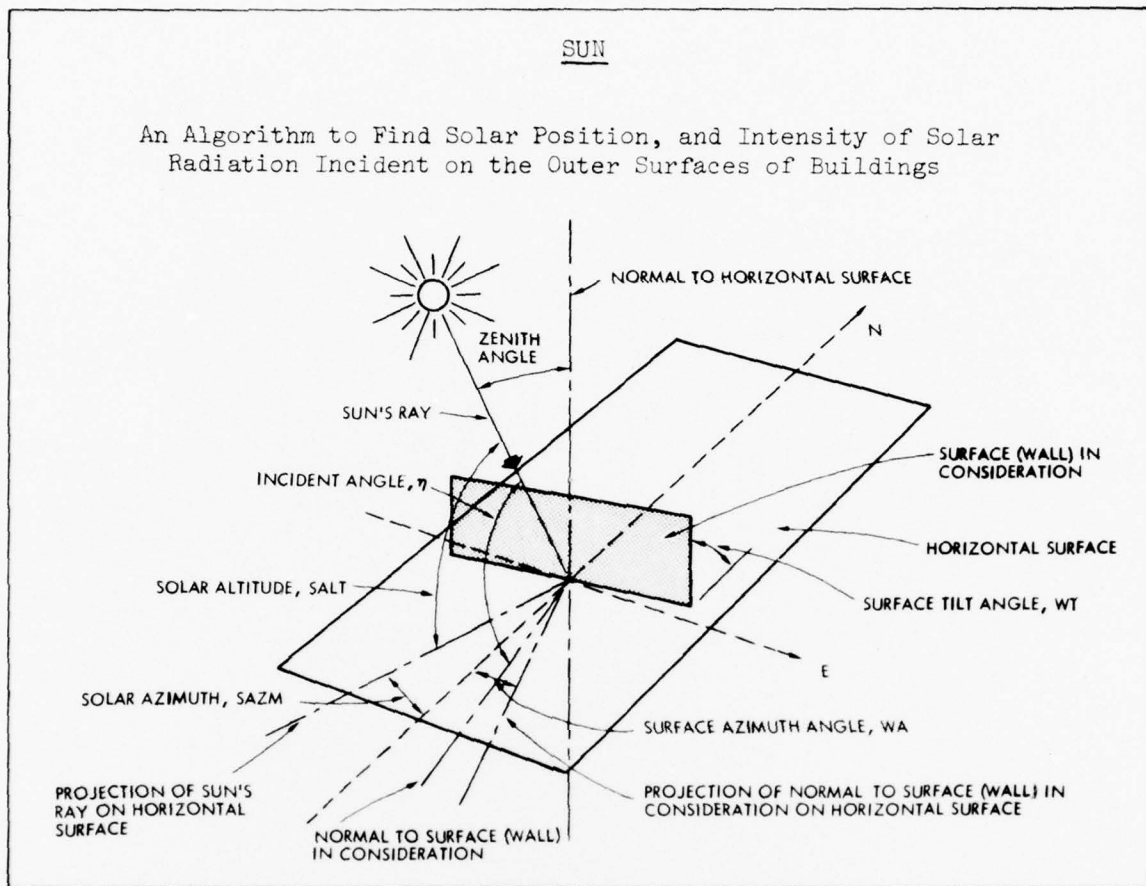
<u>SUN</u>

An Algorithm to Find Solar Position, and Intensity of Solar
Radiation Incident on the Outer Surfaces of Buildings

FIGURE B-1. DEFINITIONS OF ANGLES

<u>INPUT</u>:

L   Latitude, degrees, $\begin{bmatrix} +\text{North} \\ -\text{South} \end{bmatrix}$

ℓ Longitude, degrees, $\begin{bmatrix} +\text{West} \\ -\text{East} \end{bmatrix}$

TZN   Time zone number (hours behind Greenwich mean time) (see
      Figure B-2 and Table B-1)

d   Date, days (from start of year), (1 - 366)

t   Time, hours (after midnight), (0 - 24)

ρ_g Ground reflectivity

CCM   Cloud cover modifier (Output of CCM)
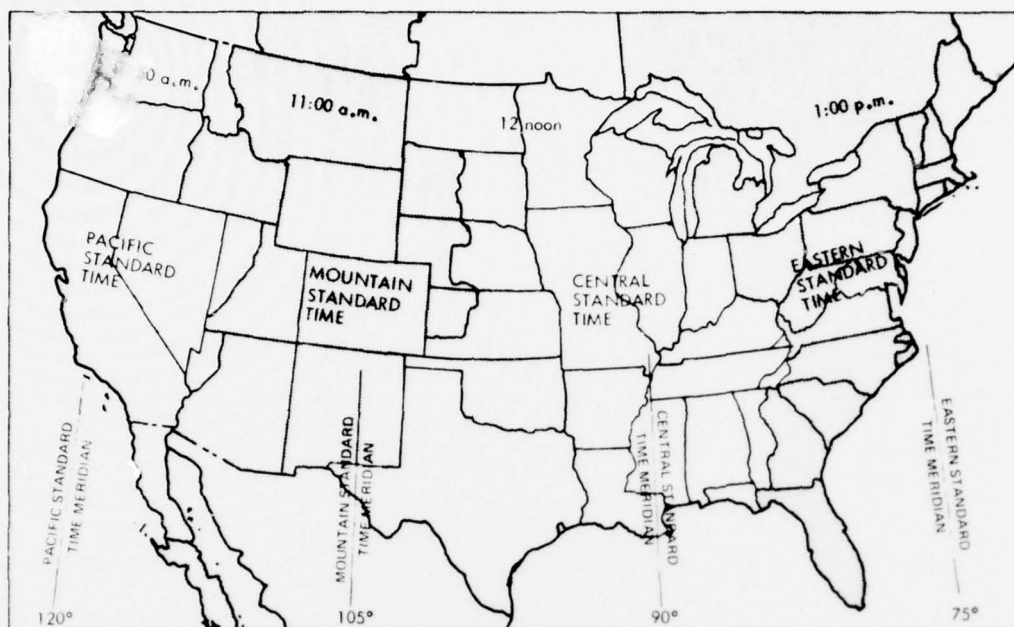
FIGURE B-2. TIME ZONES IN THE UNITED STATES

TABLE B-1.-TIME ZONE NUMBERS IN THE U.S. FOR STANDARD TIME

TIME ZONE	TZN
Atlantic	4
Eastern	5
Central	6
Mountain	7
Pacific	8

CN   Clearness number* (see Figure B-3)

WA   Surface azimuth angle, degrees (from South), $\begin{bmatrix} + \text{ if West of South} \\ - \text{ if East of South} \end{bmatrix}$

WT   Surface tilt angle, degrees (from horizontal)

---

*Depending upon type of industry in the locality, use Clearness Number between 0.7 and 0.9. Otherwise, use the Clearness Numbers of nonindustrial atmosphere which are given in Figure B-3.
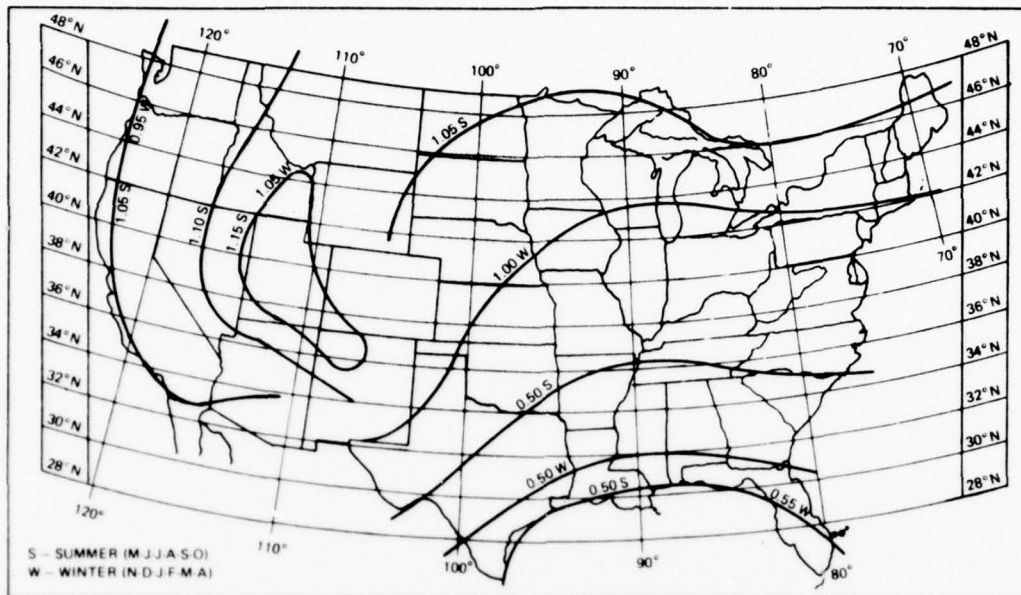
FIGURE B-3. CLEARNESS NUMBERS OF NON-INDUSTRIAL
ATMOSPHERE IN UNITED STATES

OUTPUT:

SRT)
SST)   Sunrise and sunset time, hours (after midnight)

Cos(Z))
Cos(W))   Direction cosines of direct solar beams
Cos(S))

α)
β)   Direction of cosines of normal to surface (Reference axes:
γ)   Vertical, Horizontal to West, Horizontal to South)

Cos(η)   Cosine of angle of incidence of direct solar radiation

SALT   Solar altitude, degrees

SAZM   Solar azimuth, degrees

SB   Sky brightness (= diffuse sky radiation on horizontal surface),
     Btu per (hr)(sq ft)

BG   Ground brightness (= diffuse ground reflected radiation,
     Btu per (hr)(sq ft)

IDN   Intensity of direct normal solar radiation, But per (hr)
      (sq ft)

I   Intensity of total solar radiation incident on surface (wall), Btu per (hr)(sq ft)

$I_{d,sky}$ Intensity of sky diffuse radiation incident on surface (wall), Btu per (hr)(sq ft)

$I_{d,ground}$ Intensity of ground diffuse radiation incident on surface (wall), Btu per (hr)(sq ft)

Table B-2 lists, as function of date and for the northern hemisphere only, five variables related to solar radiation. These variables are declination angle δ; the equation of time, ET; the apparent solar constnat, A; the atmospheric coefficient, B; and sky diffuse factor, C.

Table B-2 could be stored in the computer memory, but this would necessitate an interpolation procedure. In order to avoid such a problem and to save computer core space, δ, ET, A, B and C are expressed in Fourier Series form, and the values are calculated as a function of the day of the year, d, from the following truncated Fourier series.

$$\left.\begin{matrix} \delta \\ ET \\ A \\ B \\ C \end{matrix}\right\} = \begin{aligned} &A_0 + A_1 * \cos(\omega * d) + A_2 * \cos(2 * \omega * d) + A_3 * \cos(3 * \omega * d) \\ &+ B_1 * \sin(\omega * d) + B_2 * \sin(2 * \omega * d) + B_3 * \sin(3 * \omega * d) \end{aligned}$$

where $\omega = 2 * \pi/366$.

TABLE B-2.—VALUES OF δ, ET, A, B AND C

Date	δ Degrees	ET Hours	A Btu per (hr)(sq ft)	B Air Mass^{-I}	C
Jan. 21	-20.0	-0.190	390	0.142	0.058
Feb. 21	-10.8	-0.230	385	0.144	0.060
Mar. 21	0.0	-0.123	376	0.156	0.071
Apr. 21	11.6	0.020	360	0.180	0.097
May 21	20.0	0.060	350	0.196	0.121
June 21	23.45	-0.025	345	0.205	0.134
July 21	20.6	-0.103	344	0.207	0.136
Aug. 21	12.3	-0.051	351	0.201	0.122
Sept. 21	0.0	0.113	365	0.177	0.092
Oct. 21	-10.5	0.255	378	0.160	0.073
Nov. 21	-19.8	0.235	387	0.149	0.063
Dec. 21	-23.45	0.033	391	0.142	0.057

The proper Fourier coefficients are given in Table B-3.

TABLE B-3.—FOURIER COEFFICIENTS

	A_0	A_1	A_2	A_3	B_1	B_2	B_3
δ	0.302	-22.93	-0.229	-0.243	3.851	0.002	-0.055
ET	0.0	0.007	-0.05	-0.0015	-0.122	-0.156	-0.005
A	368.44	24.52	-1.14	-1.09	0.58	-0.18	0.28
B	0.1717	-0.0344	0.0032	0.0024	-0.0043	0.0	-0.0008
C	0.0905	-0.0410	0.0073	0.0015	-0.0034	0.0004	-0.0006

CALCULATION SEQUENCE:

1. Determine or calculate δ, ET, A, B, C and CCM.

2. Calculate sunrise and sunset time, h', radians.

$$h' = \cos^{-1}(-\tan(L) * \tan(\delta))$$

$$Y = h' * (12/\pi)$$

Sunrise time, SRT, hr

$$SRT = 12 - Y - ET - TZN + \ell/15$$

Sunset time, SST, hr

$$SST = 24 - SRT$$

3. Calculate hour angle, h, degrees.

$$h = 15 * (t - 12 + TZN + ET) - \ell$$

4. Check if $|h| > |h'|$.

         If yes, make I = 0 and skip following steps.
         If no, go to next step.

5. Calculate direction cosines of direct solar beams.

$$Cos(Z) = Sin(L) * Sin(\delta) + Cos(L) * Cos(\delta) * Cos(h)$$

$$Cos(W) = Cos(\delta) * Sin(h)$$

$$Cos(S) = (1 - (Cos(Z))**2 - (Cos(W))**2)**0.5$$

If $Cos(h) > (Tan(\delta)/Tan(L))$, $Cos(S)$ is positive, otherwise it is negative.

6. Calculate solar altitude and solar azimuth.

$$SALT = Sin^{-1}(Cos(Z))$$

If $Cos(S) > 0$, $SAZM = Sin^{-1}(Cos(W)/Cos(SALT))$.

If $Cos(S) < 0$, $SAZM = 180 - Sin^{-1}(Cos(W)/Cos(SALT))$.

7. Calculate intensity of direct normal solar radiation.

$$IDN = A * CN * CCM * Exp(-B/Cos(Z))$$

8. Calculate sky brightness.

$$BS = C * IDN/(CN**2)$$

9. Calculate ground brightness.

$$BG = \rho_g * (BS + IND * Cos(Z))$$

10. Calculate direction cosines of normal to surface (wall).

$$\alpha = \text{Cos}(WT)$$

$$\beta = \text{Sin}(WA) * \text{Sin}(WT)$$

$$\gamma = \text{Cos}(WA) * \text{Sin}(WT)$$

11. Calculate cosine of angle of incidence.

$$\text{Cos}(\eta) = \alpha * \text{Cos}(Z) + \beta * \text{Cos}(W) + \gamma * \text{Cos}(S)$$

12. Calculate intensity of direct solar radiation incident on surface (wall).

$$ID = IDN * \text{Cos}(\eta) \qquad \text{If Cos}(\eta) > 0, \text{ otherwise } ID = 0$$

13. Calculate intensity of sky diffuse radiation incident on surface (wall).

For Horizontal Surface:

$$I_{d,sky} = C * IDN$$

For Vertical Surface:

If $\text{Cos}(\eta) > -0.2$

$$Y = 0.55 + 0.437 * \text{Cos}(\eta) + 0.313 * (\text{Cos}(\eta)**2)$$

Otherwise $Y = 0.45$

$$I_{d,sky} = IDN * (C * Y + (\rho_g * (C + \text{Cos}(Z)))/2)$$

14. Calculate intensity of ground diffuse radiation incident on surface (wall).

$$I_{d,ground} = BG * ((1-\alpha)/2)$$

15. Calculate intensity of total solar radiation incident on surface (wall).

$$I = (ID + I_{d,sky} + I_{d,ground})$$

<u>CCM*</u>

Cloud Cover Modifier

<u>INPUT</u>:

SALT   Solar altitude angle, degrees (Output of SUN)

CT   Cloud type

$$CT = \begin{cases} 0 & \text{cirrus or cirrostratus**} \\ 1 & \text{stratus} \end{cases}$$

TC   Total cloud amount at time t

<u>OUTPUT</u>:

CCM   Cloud cover modifier

Table B-4[†] lists the value of cloud cover modifier, CCM, for each combination of cloud type, total cloud amount, and solar altitude angle. Each column of Table B-4, corresponding to a given cloud type and a solar altitude, has been expressed as a cubic relationship between total cloud amount and CCM. The resulting six equations are given in Table B-5.

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*This subroutine is a stop-gap until better information is available for the effect of cloud cover on diffuse sky radiation.

**For any other type cloud, use the mean of CCM for CT = 0 and 1.

†Derived from Boeing Company Report, Summary of Solar Radiation Observation D2-90577-1/Dec. 1964.
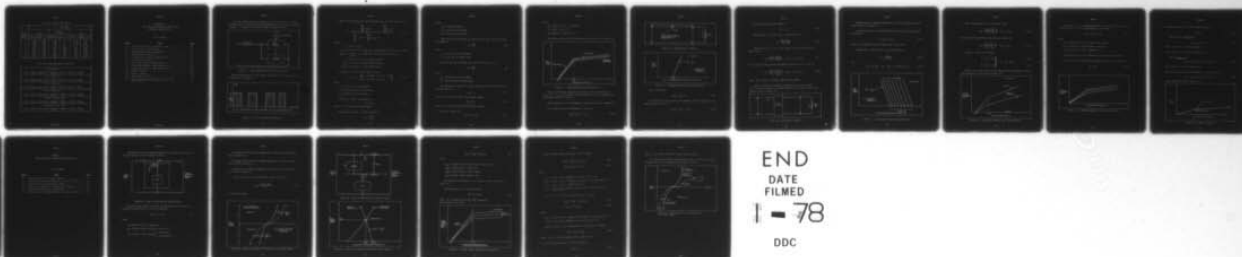
TABLE B-4.-CLOUD COVER MODIFIER

| Total Cloud Amount | Cloud Type | | | | | |
| | Stratus | | Cirrus or Cirrostratus | | Other | |
	SALT $\leq$ 45°	SALT > 45°	SALT $\leq$ 45°	SALT > 45°	SALT $\leq$ 45°	SALT > 45°
1	0.60	0.88	0.84	1.0	0.72	0.94
2	0.60	0.88	0.83	1.0	0.715	0.94
3	0.58	0.88	0.83	1.0	0.705	0.94
4	0.58	0.87	0.82	1.0	0.70	0.935
5	0.57	0.85	0.80	0.99	0.685	0.92
6	0.53	0.83	0.77	0.98	0.65	0.905
7	0.49	0.79	0.74	0.95	0.615	0.87
8	0.43	0.73	0.67	0.90	0.55	0.815
9	0.35	0.61	0.60	0.84	0.475	0.725
10	0.27	0.46	0.49	0.74	0.38	0.42

TABLE B-5.-CLOUD COVER MODIFIER EQUATIONS

CT = 0, SALT $\leq$ 45°
CCM = 0.598 + 0.00026 * TC + 0.0021 * (TC**2) - 0.00035 * (TC**3)
CT = 0, SALT > 45°
CCM = 0.908 - 0.03214 * TC + 0.0102 * (TC**2) - 0.00114 * (TC**3)
CT = 1, SALT $\leq$ 45°
CCM = 0.849 - 0.01277 * TC + 0.0036 * (TC**2) - 0.00059 * (TC**3)
CT = 1, SALT > 45°
CCM = 1.010 - 0.01394 * TC + 0.00553 * (TC**2) - 0.00068 * (TC**3)
CT $\neq$ 0 or 1, SALT $\leq$ 45°
CCM = 0.724 - 0.00652 * TC + 0.00191 * (TC**2) - 0.00047 * (TC**3)
CT $\neq$ 0 or 1, SALT > 45°
CCM = 0.959 - 0.02304 * TC + 0.00787 * (TC**2) - 0.00091 * (TC**3)

APPENDIX C
POWER CONDITIONING AND DISTRIBUTION GROUP
ELECTRICAL CHARACTERISTICS

LIST OF FIGURES

The Power Conditioning and Distribution Group (PCDG) consists of a Lamp Flasher Regulator in parallel with a Housekeeping Regulator as well as ancillary equipment. A schematic of the PCDG is shown in Figure C-1 below:
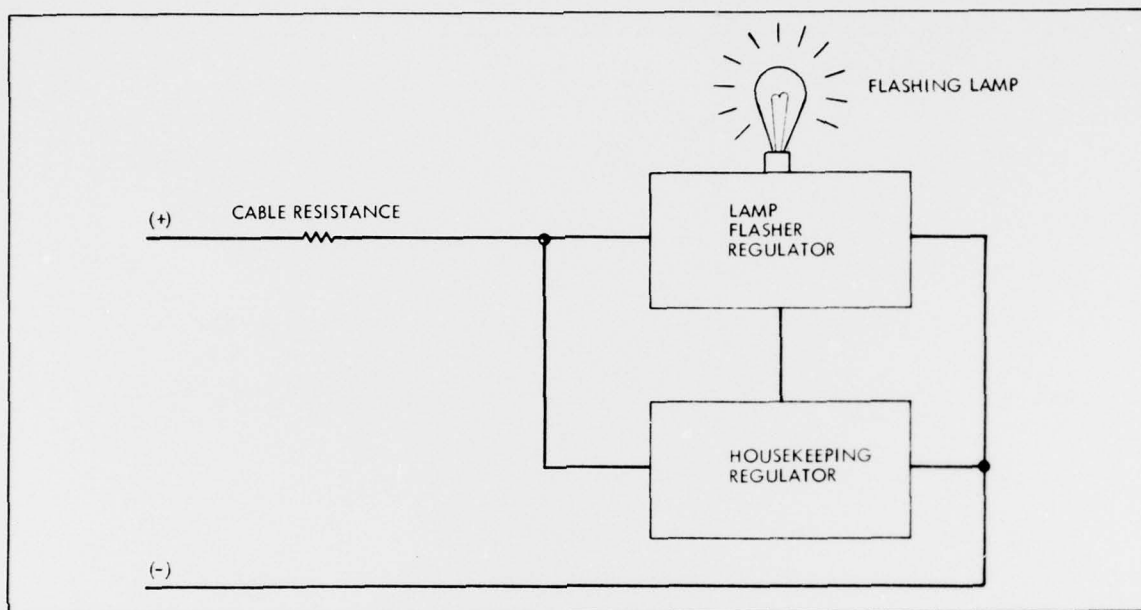
FIGURE C-1. POWER CONDITIONING AND DISTRIBUTION GROUP

Typical characteristics of the flasher which controls the lamp duty cycle are shown below in Figure C-2.

FIGURE C-2. TYPICAL FLASHER CHARACTERISTICS

Based on the characteristics shown in Figure C-2, the lamp duty cycle is:

$$D_L = \frac{\sum\limits_{i=1}^{N_{LON}} t_{LON}(i)}{\sum\limits_{i=1}^{N_{LON}} t_{LON}(i) + \sum\limits_{J=1}^{N_{LOFF}} t_{LOFF}(J)} = \frac{\sum\limits_{i=1}^{N_{LON}} t_{LON}(i)}{\tau_L} \qquad (C-1)$$

where:

D_L = Lamp duty cycle

$t_{LON}(i)$ = Duration of ith lamp flash during repetitive period, τ_L, seconds

$t_{LOFF}(J)$ = Duration of Jth lamp cutoff during repetitive period, τ_L, seconds

τ_L = Repetitive period of flasher, seconds

N_{LON} = Total number of lamp flashes during τ_L

N_{LOFF} = Total number of lamp cutoffs during τ_L

Correcting for cold filament surge at turn-on:

$$I_L = C_{LS} \ I_{LR} \quad \begin{cases} C_{LS} > 1.0 \text{ when: } (0.0 < D_L < 1.0) \\ C_{LS} = 1.0 \text{ when: } D_L = 1.0 \end{cases} \qquad (C-2)$$

where:

I_L = Actual lamp current, amperes

C_{LS} = Filament surge correction factor

I_{LR} = Rated lamp current, amperes

Finally, the average lamp current is:

$$\overline{I}_L = I_L \ D_L \qquad (C-3)$$

where: $\overline{I}_L$ = Average lamp current, amperes

The resistance rating of a lamp is given by:

$$R_{LR} = \frac{V_{LR}}{I_{LR}} \qquad (C-4)$$

where:

V_{LR} = Voltage rating, VDC

I_{LR} = Current rating, amperes

R_{LR} = Resistance rating, ohms

Using the actual lamp current (including turn-on surge), the actual lamp resistance is:

$$R_L = \frac{V_{LR}}{I_L} \qquad (C-5)$$

where:

I_L = Actual lamp current, amperes

R_L = Actual lamp resistance, ohms

The effective lamp resistance (due to an on-off duty cycle) is:

$$\overline{R}_L = \frac{V_{LR}}{\overline{I}_L} \qquad (C-6)$$

where:

$\overline{I}_L$ = Average lamp current, amperes

$\overline{R}_L$ = Effective lamp resistance, ohms

The lamp-flasher regulator is a series regulator and hence has the following characteristics.

$$I_{RI} = I_L \qquad (C-7)$$

where: I_{RI} = Actual regulator input current, amperes

$$\overline{I}_{RI} = \overline{I}_L \qquad (C-8)$$

where: $\overline{I}_{RI}$ = Average regulator input current, amperes

While the voltages are:

$$V_L = F\{V_{RI},\ T_R\} \qquad (C-9)$$

where:

V_{RI} = Regulator input voltage, VDC

V_L = Lamp voltage, VDC

T_R = Regulator temperature, °F

The regulator characteristics of the lamp-flasher are shown in Figure C-3.
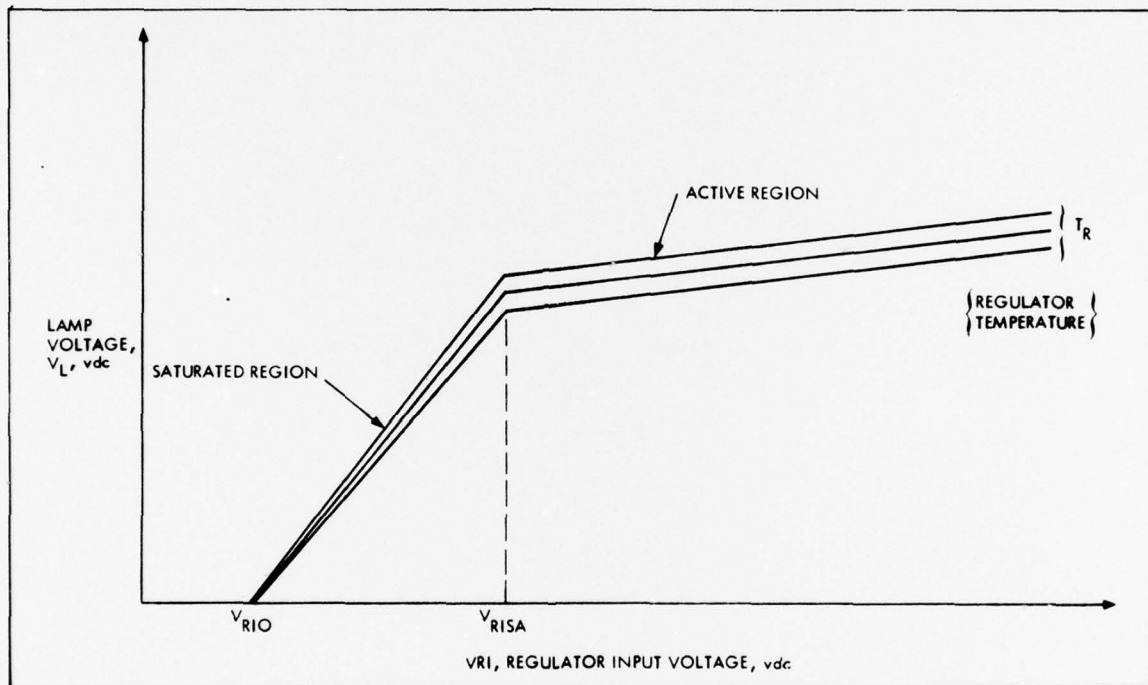
FIGURE C-3.   LAMP-FLASHER REGULATOR CHARACTERISTICS

When the lamp-flasher regulator is operating in the saturated region ($V_{RIO} < V_{RI} < V_{RISA}$), the regulator and lamp combination may be represented by the schematic shown in Figure C-4.

The characteristics of a saturated pass transistor are shown in Figure C-5.

The voltage drop across the regulator is given by:

$$\Delta V_{RS} = V_{RIO} + I_L \, Z_{RS} \tag{C-10}$$
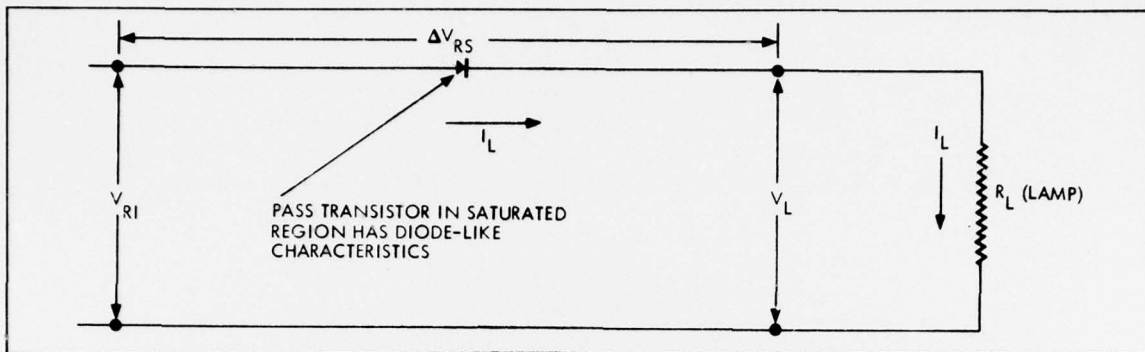
FIGURE C-4.   SATURATED REGION OPERATION
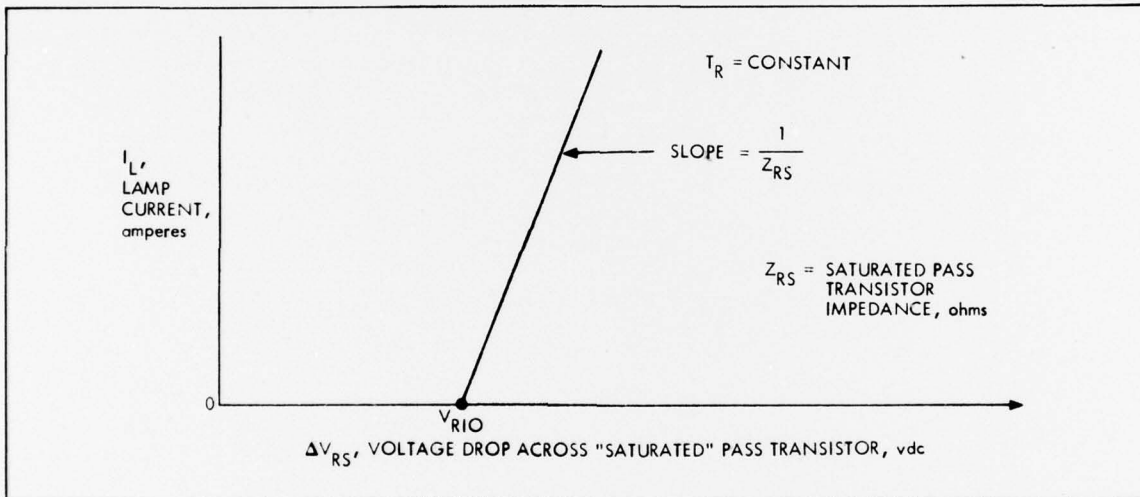
FIGURE C-5.   SATURATED PASS TRANSISTOR CHARACTERISTICS

But, by definition:

$$\Delta V_{RS} = V_{RI} - V_L \tag{C-11}$$

Combining Eqs. (C-10) and (C-11), the regulator output voltage (i.e., the lamp voltage) is given by:

$$V_L = V_{RI} - V_{RIO} - I_L Z_{RS} \tag{C-12}$$

The voltage drop across the lamp is:

$$V_L = I_L R_L \qquad \text{(C-13)}$$

Combining Eqs. (C-12) and (C-13), the lamp current is:

$$I_L = \frac{V_{RI} - V_{RIO}}{R_L + Z_{RS}} \qquad \text{(C-14)}$$

Substituting Eq. (C-7) into (C-14) yields, for the actual regulator input current:

$$I_{RI} = \left(\frac{V_{RI} - V_{RIO}}{R_L + Z_{RS}} \right) \; ; \quad (V_{RIO} < V_{RI} \leq V_{RISA}) \qquad \text{(C-15)}$$

and by using the same methods, the effective regulator input current is:

$$\overline{I}_{RI} = \left(\frac{V_{RI} - V_{RIO}}{\overline{R}_L + Z_{RS}} \right) \; ; \quad (V_{RIO} < V_{RI} \leq V_{RISA}) \qquad \text{(C-16)}$$

where: $\overline{I}_{RI}$ = Effective regulator input current, amperes

When the lamp-flasher regulator is operating in the active region (VRI > VRISA), the regulator and lamp combination may be represented by the schematic shown in Figure C-6.
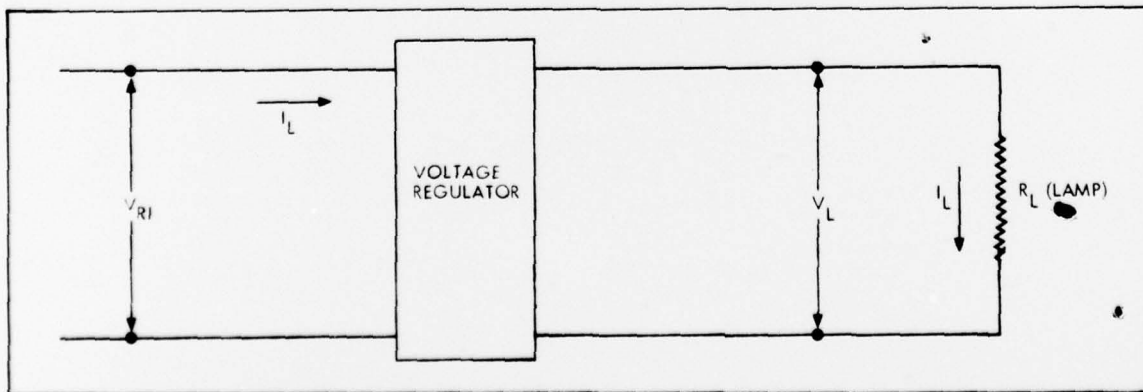
FIGURE C-6. ACTIVE REGION OPERATION

Voltage regulator output characteristics in the "pass transistor active" region are shown in Figure C-7.

In the active region, it may be shown that the regulator characteristics are given by:

$$V_L = V_{LB} - I_L Z_{RA} \qquad (C-17)$$

where: V_{LB} = Regulator output voltage at zero current, VDC

Combining Eqs. (C-13) and (C-17), the lamp current is:

$$I_L = \frac{V_{LB}}{R_L + Z_{RA}} \qquad (C-18)$$

But:

$$V_{LB} = V_{LB} \{V_{RI}\} \quad \text{i.e.:} \quad V_{LB} \text{ is a function of } V_{RI} \qquad (C-19)$$
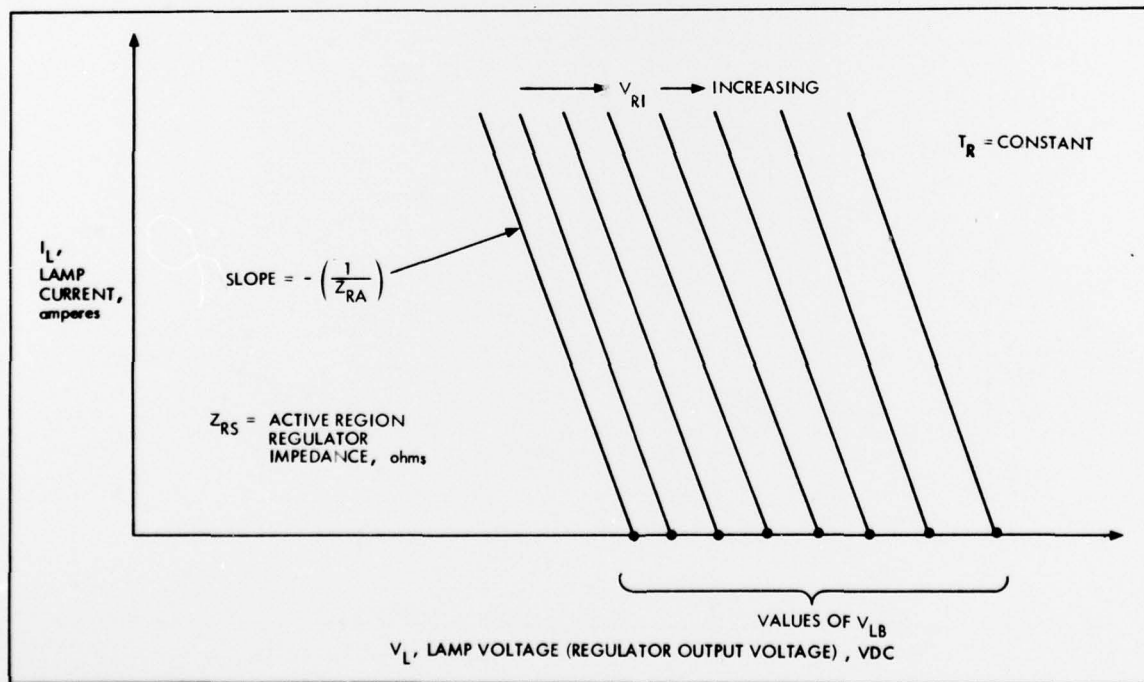
FIGURE C-7.   ACTIVE REGION REGULATOR CHARACTERISTICS

Hence, combining Eqs. (C-7), (C-18) and (C-19):

$$I_{RI} = \left(\frac{V_{LB} \{V_{RI}\}}{R_L + Z_{RA}} \right); \quad (V_{RI} > V_{RISA}) \tag{C-20}$$

and by using the same methods, the effective currents are:

$$\overline{I}_{RI} = \left(\frac{V_{LB} \{V_{RI}\}}{\overline{R}_L + Z_{RA}} \right); \quad (V_{RI} > V_{RISA}) \tag{C-21}$$

Finally, it should be noted when

$$I_L = I_{RI} = 0.0 \tag{C-22}$$

$$; \quad (0 < V_{RI} < V_{RIO})$$

$$\overline{I}_L = \overline{I_{RI}} = 0.0 \tag{C-23}$$

Based on the foregoing derivations, the generalized lamp-flasher regulator input characteristics are shown in Figure C-8.
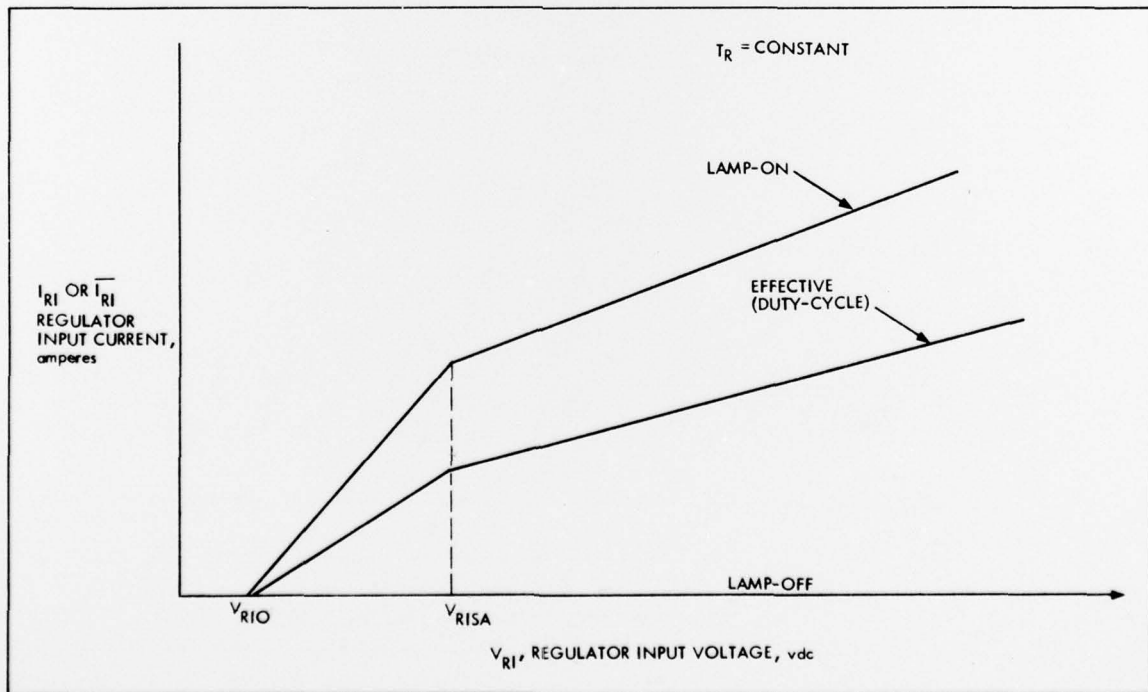
FIGURE C-8. LAMP-FLASHER REGULATOR INPUT CHARACTERISTICS

At the input to the housekeeping regulator (a series regulator), which is in parallel with the lamp-flasher regulator, the current is:

$$I_{HI} = I_{HI} \{V_{HI}, T_H\} \tag{C-24}$$

where:

I_{HI} = Housekeeping regulator input current, amperes

V_{HI} = Housekeeping regulator input voltage, VDC

T_H = Housekeeping regulator temperature, $^\circ$F

The housekeeping regulator characteristics are shown in Figure C-9.

Since both the lamp-flasher and housekeeping regulators are in parallel:

$$V_{HI} = V_{RI} \tag{C-25}$$
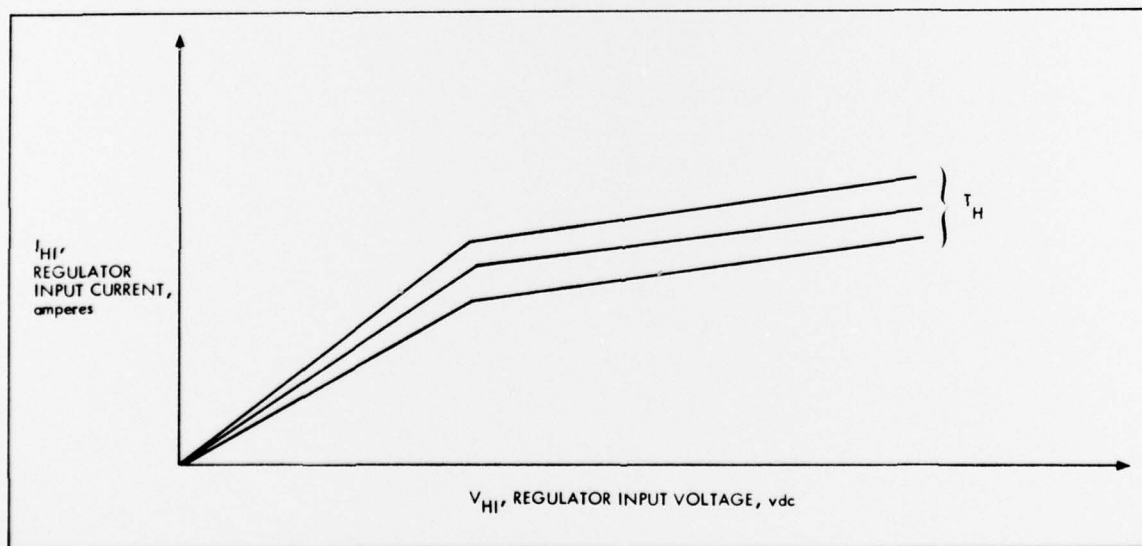
FIGURE C-9.   HOUSEKEEPING REGULATOR INPUT CHARACTERISTICS

and since regulators are located in the same module

$$T_H = T_R \qquad (C-26)$$

Hence, when the <u>lamp is off</u>:

$$I_{UL} = I_{HI} \{V_{RI}, T_R\} \qquad (C-27)$$

where: I_{UL} = User load current, amperes

which condition is illustrated in Figure C-10.

When the <u>lamp is on</u>:

$$I_{UL} = I_{HI} \{V_{RI}, T_R\} + I_{RI} \{V_{RI}, T_R\} \qquad (C-28)$$

which condition is shown in Figure C-11.

while the average user load current while the lamp is flashing is:

$$I_{UL} = I_{HI} \{V_{RI}, T_R\} + \overline{I}_{RI} \{V_{RI}, T_R\} \qquad (C-28)$$

which condition is given in Figure C-12.
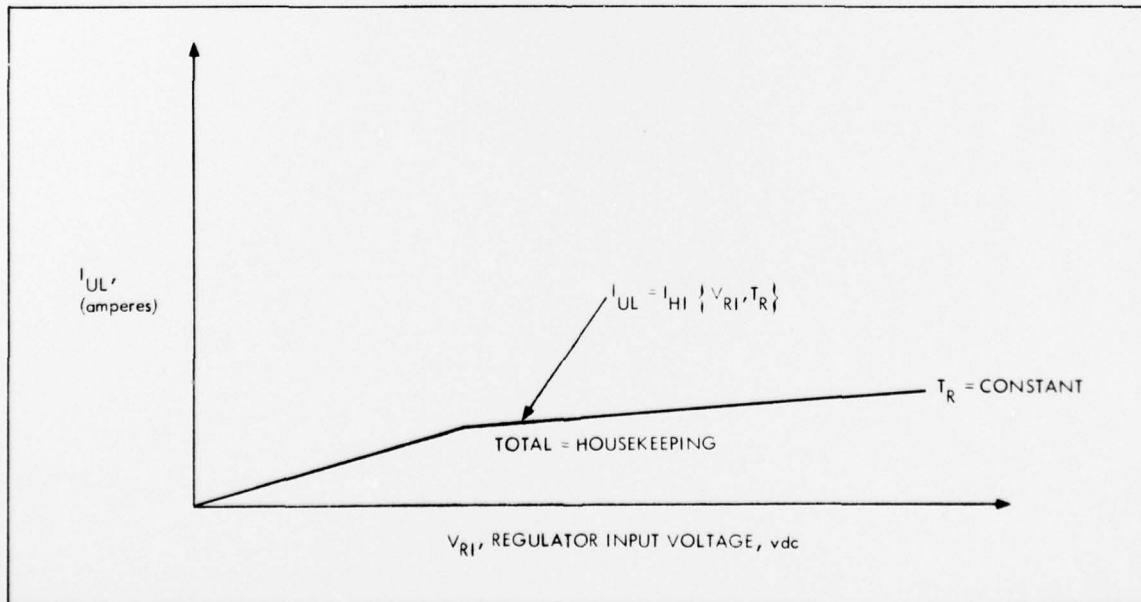
FIGURE C-10. LAMP-OFF CONDITION
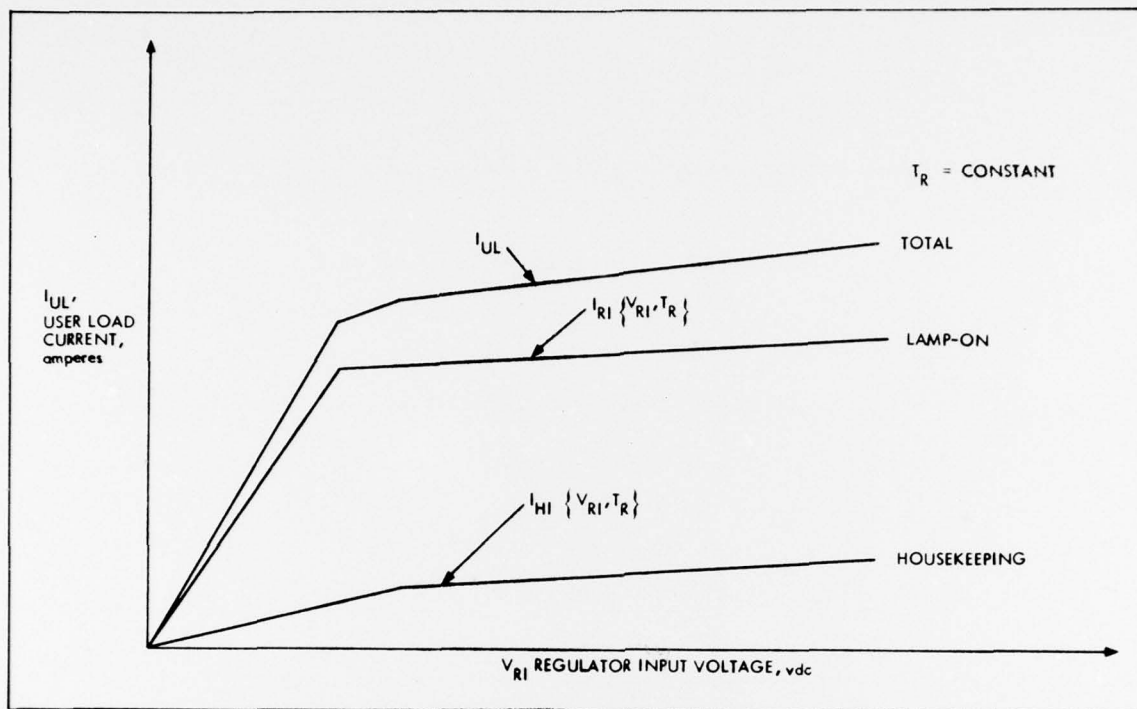
FIGURE C-11.   LAMP-ON CONDITION
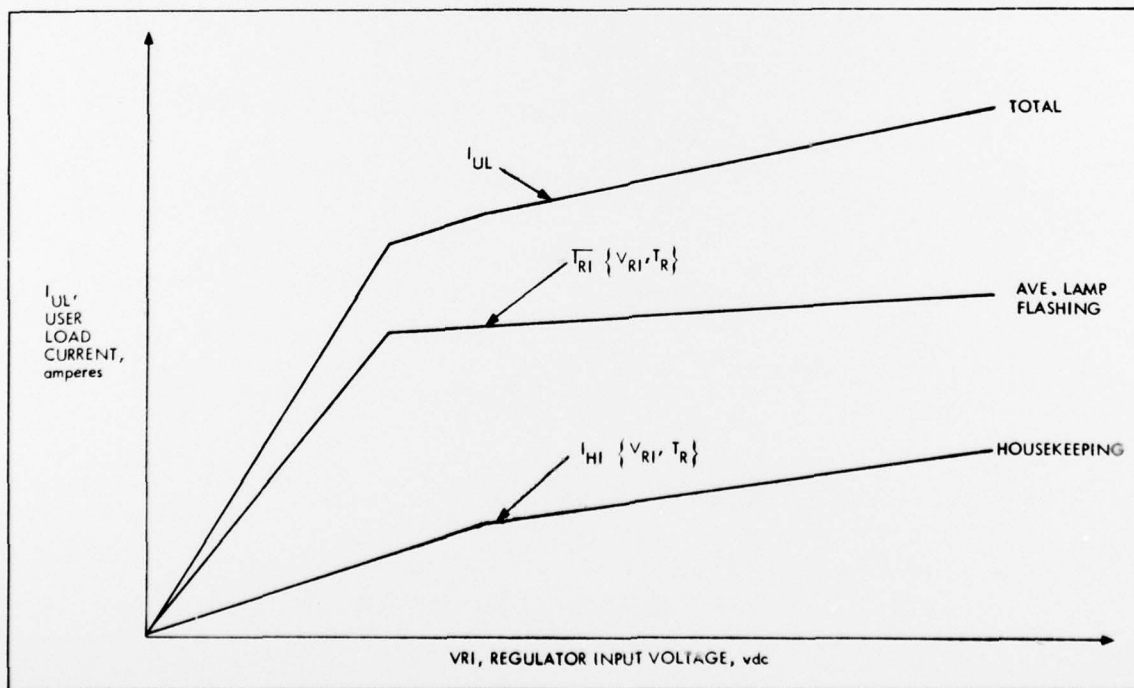
FIGURE C-12.   LAMP-FLASHING CONDITION

Since the Lamp Flasher Unit (user load) is in series with the user load cable:

$$I_{PCD} = I_{UL} \qquad\qquad (C-29)$$

where: I_{PCD} = Power Conditioning and Distribution Group current, amperes

$$V_{PCD} \{I_{PCD}, T_R\} = V_{RI} \{I_{PCD}, T_R\} + I_{PCD} R_{PCD} \qquad (C-30)$$

where:

V_{PCD} = Power Conditioning and Distribution Group input voltage, VDC

R_{PCD} = User load cable resistance, ohms

The characteristics of the power conditioning group, based on Eqs. (C-29) and (C-30), are shown graphically in Figure C-13.
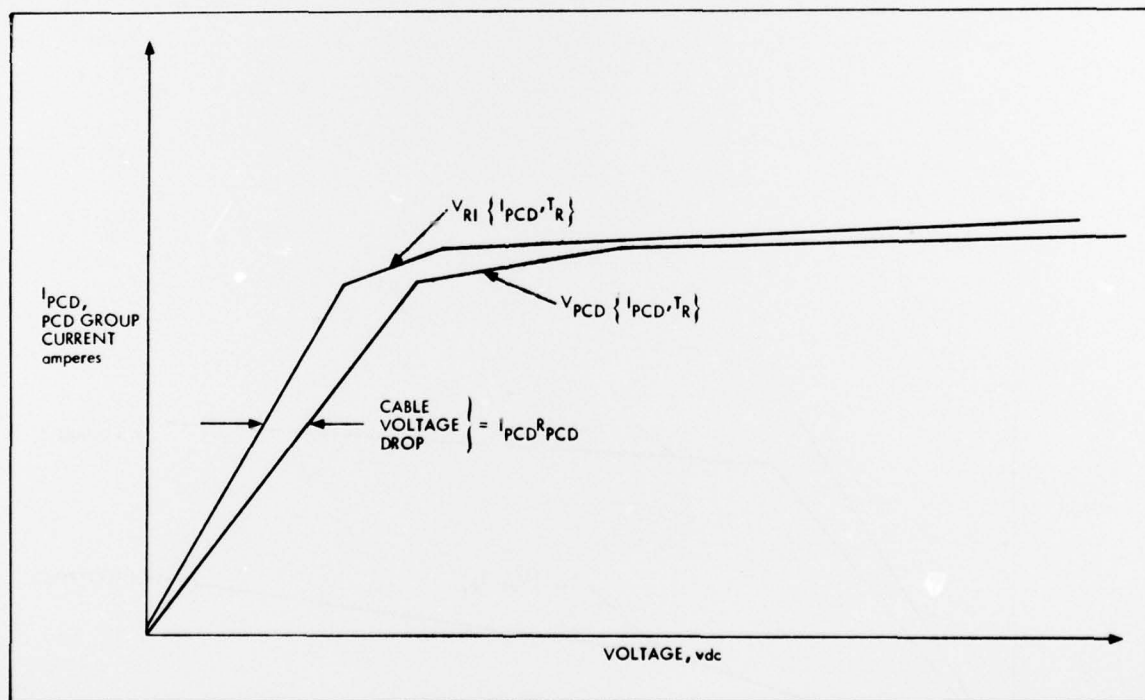
FIGURE C-13. POWER CONDITIONING AND DISTRIBUTION GROUP INPUT CHARACTERISTICS

APPENDIX D

ENERGY STORAGE UNIT ELECTRICAL CHARACTERISTICS

LIST OF FIGURES

The simplest form of the Energy Storage Unit in relation to the rest of the power system is shown in Figure D-1 below.
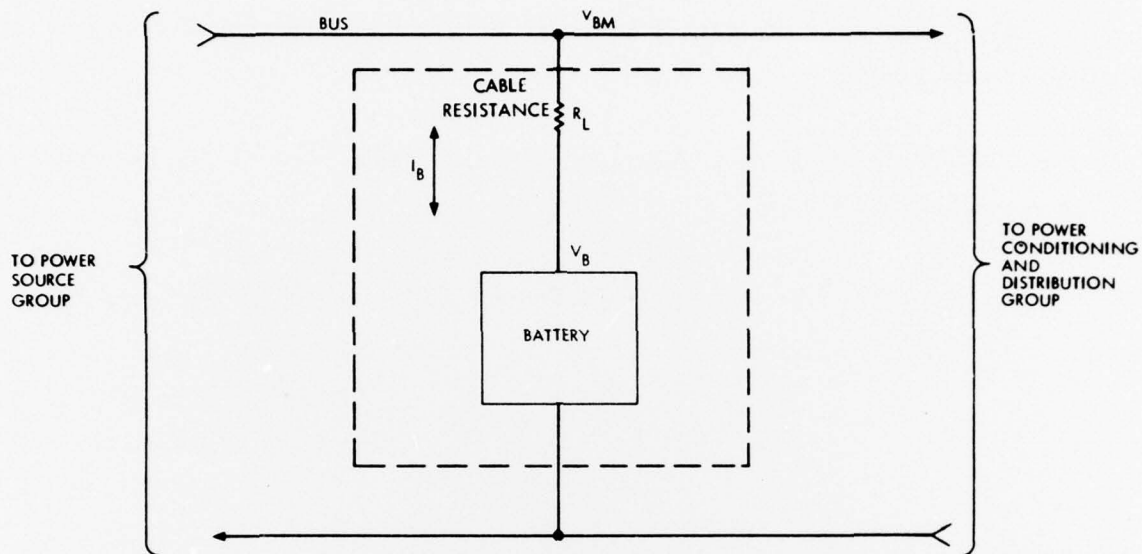

FIGURE D-1.   ENERGY STORAGE UNIT, NO BATTERY CHARGER

The relationship between the battery voltage and the bus voltage (or the battery voltage reflected to the bus) is given by:

$$V_{BM} \equiv V_B + I_B R_L \qquad \text{(D-1)}$$

where:

V_B = Battery terminal voltage, VDC

V_{BM} = Battery voltage reflected to the bus, VDC

I_B = Battery current, amperes $\begin{cases} + = \text{charge mode} \\ - = \text{discharge mode} \end{cases}$

The Energy Storage Unit input characteristics under these conditions is shown in Figure D-2.

An Energy Storage Unit with a battery charger and a battery discharge diode is shown in Figure D-3.

During periods of battery charging, the operating point on the battery bus is shown in Figure D-4.

It may be shown that the operating point current is given by:

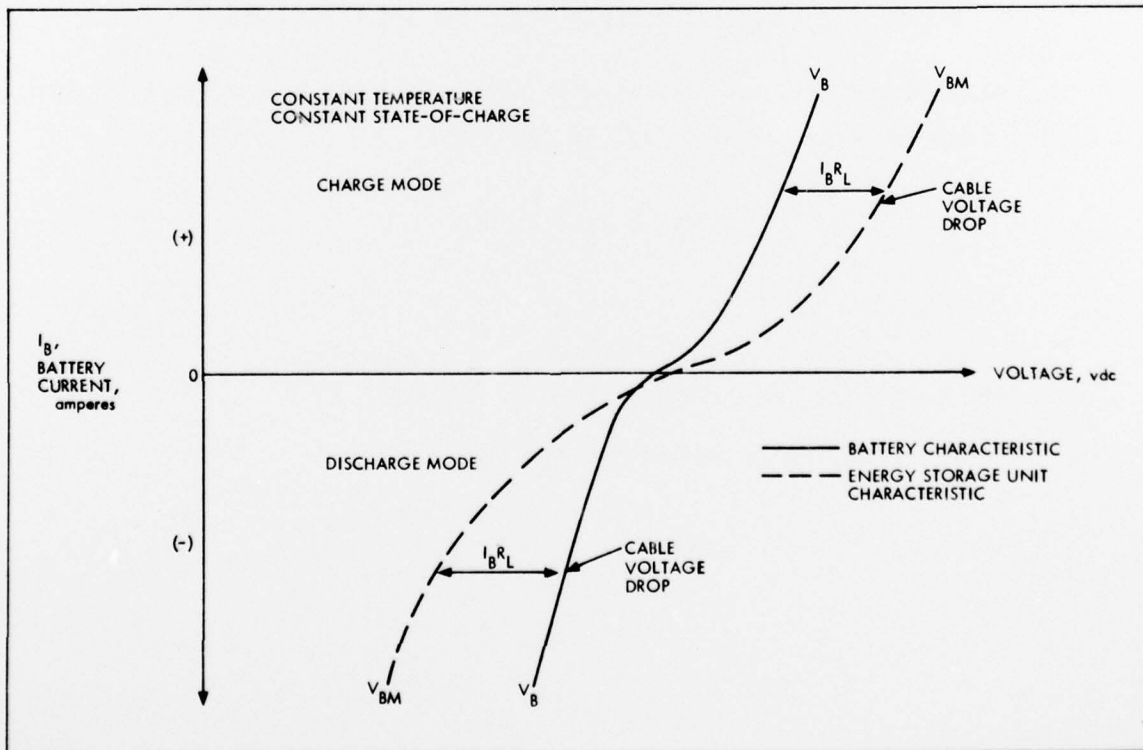$$I_{BBM} = \frac{V_{CHOO} - V_{BBM}}{Z_{CHR}} \qquad (D-2)$$

or, after rearranging:

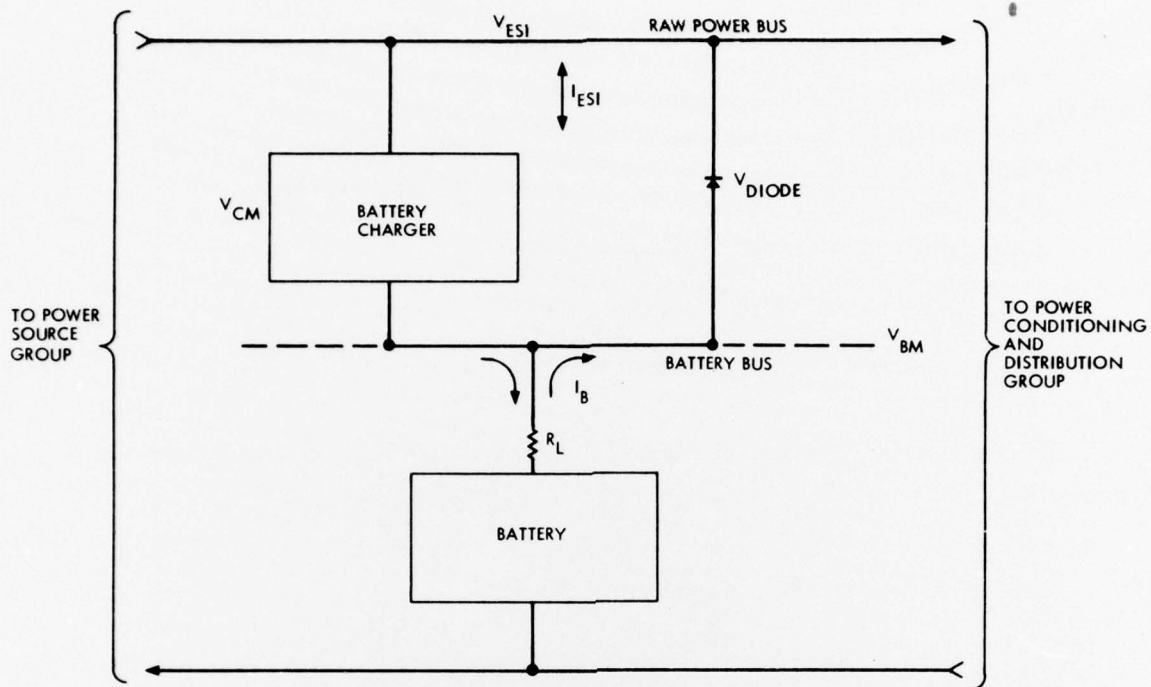FIGURE D-2.   ENERGY STORAGE UNIT CHARACTERISTICS, NO BATTERY CHARGER

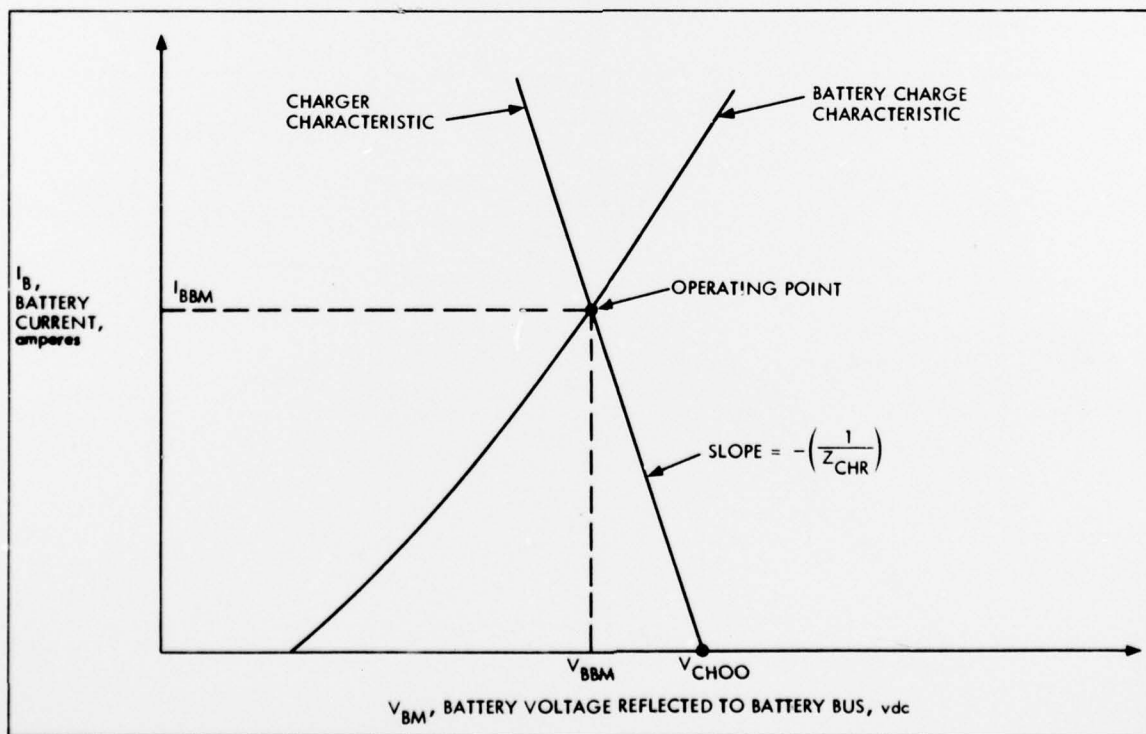FIGURE D-3.   ENERGY STORAGE UNIT, WITH BATTERY CHARGER

FIGURE D-4.   BATTERY BUS OPERATING POINT DURING BATTERY CHARGING

$$V_{CHOO} = V_{BBM} + I_{BBM} Z_{CHR} \qquad (D-3)$$

where:

V_{CHOO} = Charger output voltage at zero current, amperes

V_{BBM} = Operating point voltage, VDC

I_{BBM} = Operating point current, amperes

Z_{CHR} = Charger output impedance, ohms

The regulation characteristics of the battery charger are shown in Figure D-5.

Examining Figure D-5, it can be seen that:

$$VESI = \phi \{VCHOO\} \qquad (D-4)$$

where: VESI = Energy Storage Unit input voltage, VDC
and referring to Eq. (D-3).
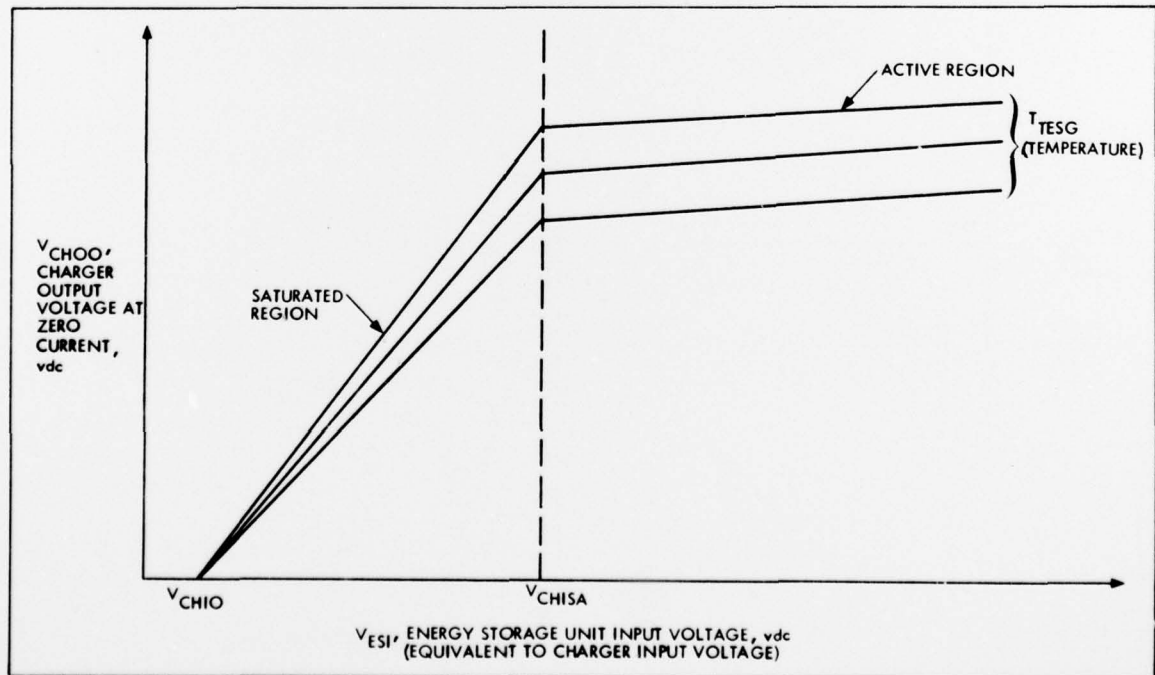

FIGURE D-5. BATTERY CHARGER REGULATION CHARACTERISTICS

In the saturated region, when $(V_{CHIO} < VESI \leq V_{CHISA})$:

$$V_{CHOOS} = V_{BBM} + I_{BBM} Z_{CHRS} \tag{D-5}$$

$$V_{ESI} = V_{CHOOS} + V_{CHIO} \tag{D-6}$$

where:

Z_{CHRS} = Charger output impedance in saturated region, ohms

V_{CHOOS} = Charger output voltage at zero current in saturated region, VDC

V_{CHIO} = Input voltage at charger turn-on, VDC

V_{CHISA} = Charge input voltage at changeover from saturated to active operation, VDC

While in the active region of operation; $(V_{ESI} > V_{CHISA})$:

$$V_{CHOOA} = V_{BBM} + I_{BBM} Z_{CHRA} \tag{D-7}$$

$$V_{ESI} = \phi \{V_{CHOOA}\} \tag{D-8}$$

where:

V_{CHOOA} = Charger output voltage at zero current in active region, VDC

Z_{CHRA} = Charge output impedance in the active region, ohms

Examining Figure D-3, it can be seen that during battery discharge

$$V_{ESI} = V_{BM} - V_{DIODE} \tag{D-9}$$

where: V_{DIODE} = Battery discharge diode voltage drop, VDC

and since the battery charger is a series regulator:

$$I_{ESI} = I_B \tag{D-10}$$

where: I_{ESI} = Energy Storage Unit input current, amperes

The input characteristics of the energy storage unit based on Eqs. (D-5) through (D-10) are shown graphically in Figure D-6, below:
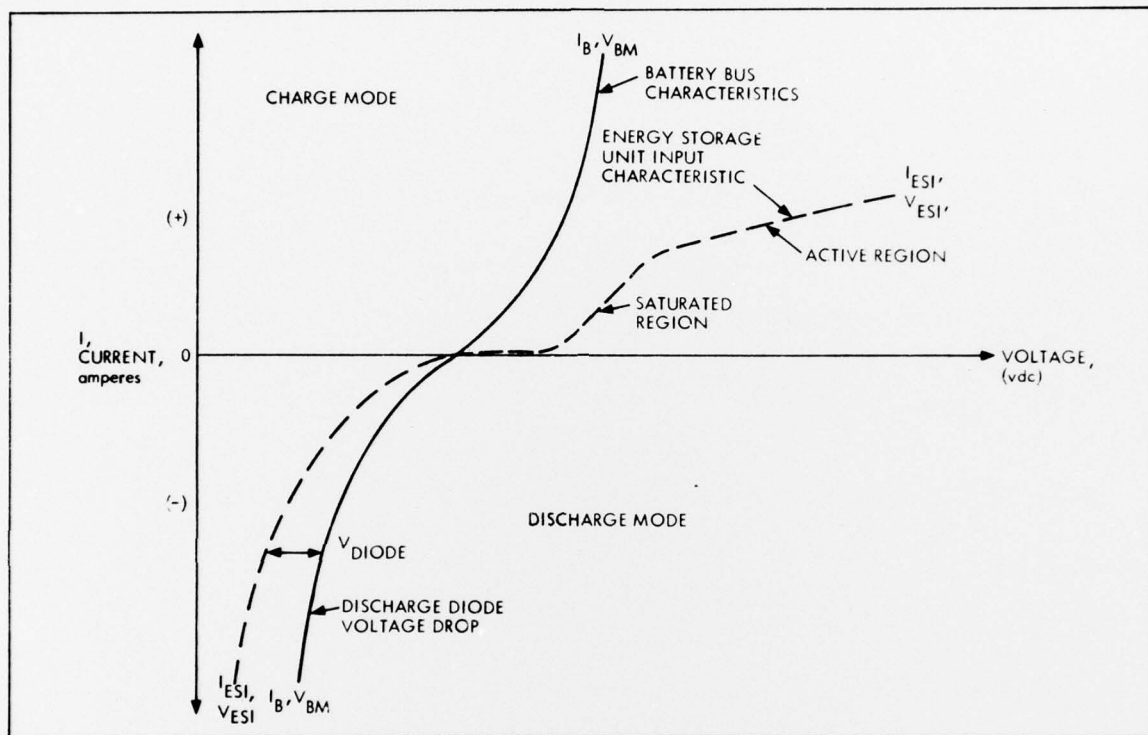

FIGURE D-6. ENERGY STORAGE UNIT CHARACTERISTICS, WITH BATTERY CHARGER